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ENERGY EFFICIENT ENGINE

CONTROLS AND ACCESSORIES DETAIL DESIGN REPORT

by

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Prepared by

GENERAL ELECTRIC COMPANY

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16. Abstract

An Energy Efficient Engine (E^3) program has been established by NASA to develop technology for improving the energy efficiency of future commercial transport aircraft engines. As part of this program, General Electric is designing a new turbofan engine. This report describes the fuel and control system for this engine. The system design is based on many of the proven concepts and component designs used on the General Electric CF6 family of engines. One significant difference is the incorporation of digital electronic computation in place of the hydromechanical computation currently used.

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Nomenclature Definitions

A-D A-to-D	Analog to Digital Converter
AIS	Aircraft Interface Simulator
E^3	Energy Efficient Engine
EPR	Engine Pressure Ratio
FICA	Failure Indication and Corrective Action
FPS	Flight Propulsion System
Fn	Net Thrust
HP	High Pressure
HPT	High Pressure Turbine
Hz	Frequency in Hertz
ICLS	Integrated Core, Low Spool
IGV	Inlet Guide Vanes
LP	Low Pressure
LPT	Low Pressure Turbine
LVPT	Linear Variable Phase Transducer
M_{11}	Engine Inlet Mach Number
MCM	Multilayer Circuit Module
M_p	Airplane Mach Number
MUX	Multiplex (Single Path, Multiple Signal Electrical Transmission Circuit)
MZSOV	Main Zone Shutoff Valve (Fuel)
N1	Fan Rotary Speed
N2	Core Rotary Speed

Nomenclature Definitions (Continued)

P_{amb}, P_o	Ambient Pressure
PTO	Freestream Total Pressure
P25	Compressor Inlet Pressure
PS3	Compressor Discharge Static Pressure
P8	Exhaust Nozzle Inlet Total Pressure
PCNHR	Percent Corrected Core RPM $(N2/\sqrt{\theta 25})$
PCNLR	Percent Corrected Fan RPM $(N1/\sqrt{\theta 12})$
PLA	Power Lever Angle
PROM	Programmable Read-Only Memory
PTT	Pressure Transducer Temperature
QCSEE	Quiet, Clean, Short-Haul Experimental Engine
RAM	Random Access Memory
ROM	Read-Only Memory
RTD	Resistance Temperature Detector
RVPT	Rotary Variable Phase Transducer
SFC	Specific Fuel Consumption
SLS	Sea Level Static
SRTC	Start Range Turbine Cooling
T1, T12	Fair Inlet Temperature
T25	Compressor Inlet Temperature
T3	Compressor Discharge Temperature
T41	HP Turbine Inlet Temperature

Nomenclature Definitions (Concluded)

T42	HP Turbine Discharge Temperature
T49	LP Turbine Inlet Temperature
TP1, TP2, etc.	Thrust Parameters in Control Mode Study
TTL	Transistor-Transistor Logic
WFE	Engine Fuel Flow
WHRS	Waste-Heat Recovery System
XM2A	Engine Inlet Mach Number
XNHR	Core Corrected RPM ($N2/\sqrt{\theta 25}$)
$\theta 12$	T12 in Degrees Rankine/518.7
$\theta 25$	T12 in Degrees Rankine/518.7

1.0 SUMMARY

An Energy Efficient Engine (E^3) Program has been established by NASA to develop a technology for improving the energy efficiency of future commercial transport aircraft. As a part of this program, General Electric is designing and testing a new turbofan engine. This report describes the design of the control and fuel system for the General Electric E^3.

The control and fuel system for the E^3 is based on many of the proven concepts and component designs used on the CF6 engine family. One significant difference is the incorporation of digital electronic computation in place of the hydromechanical computation used on current transport aircraft engines. The timesharing capabilities of the digital computer can accommodate the additional control functions required for the E^3 without computer hardware duplication. The improved accuracy and flexibility of digital computation permits engine control strategies that improve efficiency and reduce deterioration. The digital control also offers improved aircraft/engine integration capability.

For the E^3 ICLS (integrated core/low spool) demonstrator, the system performs nine control functions. It controls fuel flow, fuel flow split (to two combustor zones), compressor stators, compressor starting bleed, start range turbine cooling, and four independent clearance control air valves. The system also provides condition monitoring data. For the core engine test that precedes the ICLS, system functions are the same except that the compressor stator control function is deleted (stages are set individually by a test facility control system for experimental flexibility) and all fan/fan turbine-related functions are deleted. The system for a production engine would be the same as for the ICLS with the addition of ignition and thrust reverser control.

System components for the demonstrator engines include (1) the digital control (which is a modification of a design produced under the Navy FADEC program, (2) a modified F101 fuel pump and control, (3) modified CF6 stator actuators, (4) modified F101 IGV actuators for air valve actuation, (5) a

number of air valves modified from existing designs, and (6) several custom-designed components including fuel flow split control valves, control mode transfer valves, and a compressor clearance control air valve. An off-engine digital control will be used for the core engine, whereas an on-engine design will be used for the ICLS. For a production E^3, dual redundant digital controls would be used initially, but it is anticipated that in-service development will produce a digital control with reliability equivalent to current controls so that ultimately a single-channel control will suffice.

2.0 INTRODUCTION

The Energy Efficient Engine (E^3) Program is a program established by NASA to develop a technology that will improve the energy efficiency of propulsion systems for subsonic commercial aircraft of the later 1980's and early 1990's. The specific major objectives of the program are to develop a technology that will provide at least a 12% improvement in cruise specific fuel consumption and a 5% improvement in direct operating cost relative to a current commercial aircraft engine, the CF6-50C. These improvements are to be achieved within the restraints of strict new noise limits as given in FAR-Part 36 (7/78 revision) and emissions limits are given in the 1/81 EPA standard for such engines.

Beyond the overall program objectives, design objectives also were established for the various elements of the E^3. For the fuel and control system, the primary objective is to define a system that thoroughly exploits the engine's fuel conservation features, provides operational capability and reliability equal to or better than current transport engine control systems, and employs digital electronic computation suitable for interfacing with aircraft propulsion and flight control computers. The system thus defined is to be demonstrated on the full-scale core and ICLS (integrated core/low spool) test engines which are a part of the E^3 program.

This report describes the control and fuel system design that has evolved for the E^3. Emphasis is placed on the system that is being built for the ICLS engine. System differences for the core engine are noted, and projected differences for a production design also are briefly addressed.

3.0 CONTROL AND FUEL SYSTEM REQUIREMENTS

The E^3 control and fuel system is designed to meet several contractually specified general design requirements established during the preliminary design phase of the program and to meet functional requirements established by the nature of the engine itself (Figure 1 cross section). These requirements are given below.

3.1 GENERAL DESIGN REQUIREMENTS

Digital Computation - The system shall employ digital electronic computation rather than the hydromechanical computation used in current transport engine controls. This conclusion was reached in E^3 preliminary design studies because the digital computer provides more scheduling flexibility of controlled variables; has timesharing capability so that many control functions can be performed without computer hardware duplication; can interface directly with aircraft system computers which, by the late 1980's, will also be digital; and offers the promise of lower cost by taking advantage of rapid electronics industry advances in circuit integration and automated manufacture.

Aircraft Interfacing - In conjunction with the previous requirement, the system shall be designed to interface with a typical aircraft control computation system.

Power Management - The system shall incorporate power management capability which automatically optimizes performance with minimum flight crew input.

Sensor/Actuator Failure Tolerance - Computational techniques shall be employed to make the system generally insensitive to failures in digital control input sensors and output actuators so that redundancy of these elements is not necessary.

Reliability - System reliability by the time of introduction into service shall be equal to or better than the reliability achieved with current

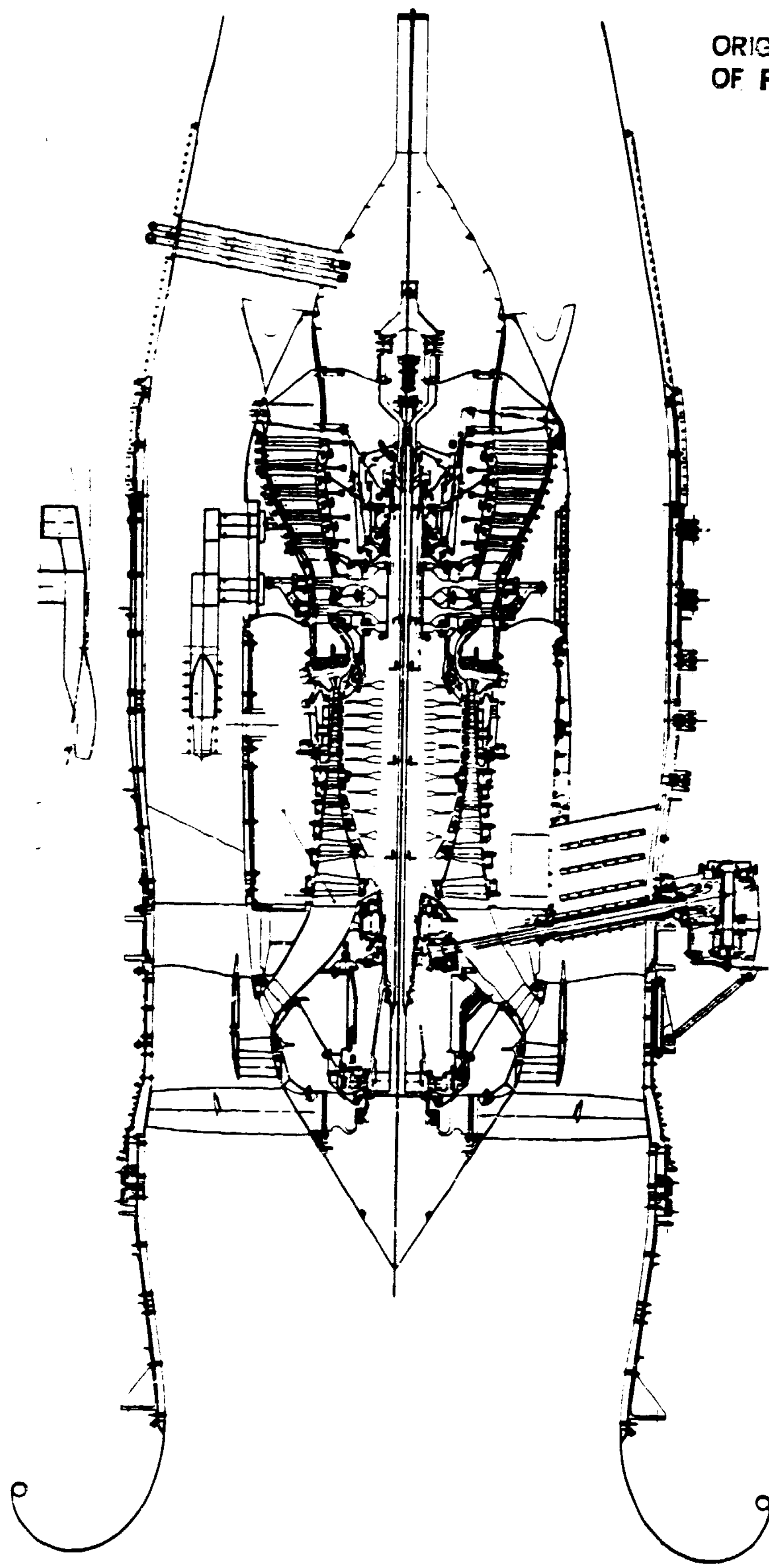

Figure 1. E^3 ICLS Engine Cross Section.

transport engine hydromechanical control systems. In a sense, this requires improved reliability because the E^3 system performs more control functions.

3.2 FUNCTIONAL DESIGN REQUIREMENTS

The design of the E^3 ICLS requires that the control system have outputs as shown on Figure 2 and that it perform the following functions:

- Modulate fuel flow to control thrust.
- Split fuel flow to the two zones of the double-annular combustor.
- Position core compressor variable stators for best compressor performance.
- Position air valves for independent active clearance control of the compressor (Stages 6-10) and the HP and LP turbines.
- Position the start bleed valves for control of core compressor 7th stage air bleed in the starting region.
- Provide on/off control of the start range turbine cooling valves which shift the cooling air source to account for reduced pressure when the starting bleed is flowing.
- Provide condition monitoring data to the engine operating crew.

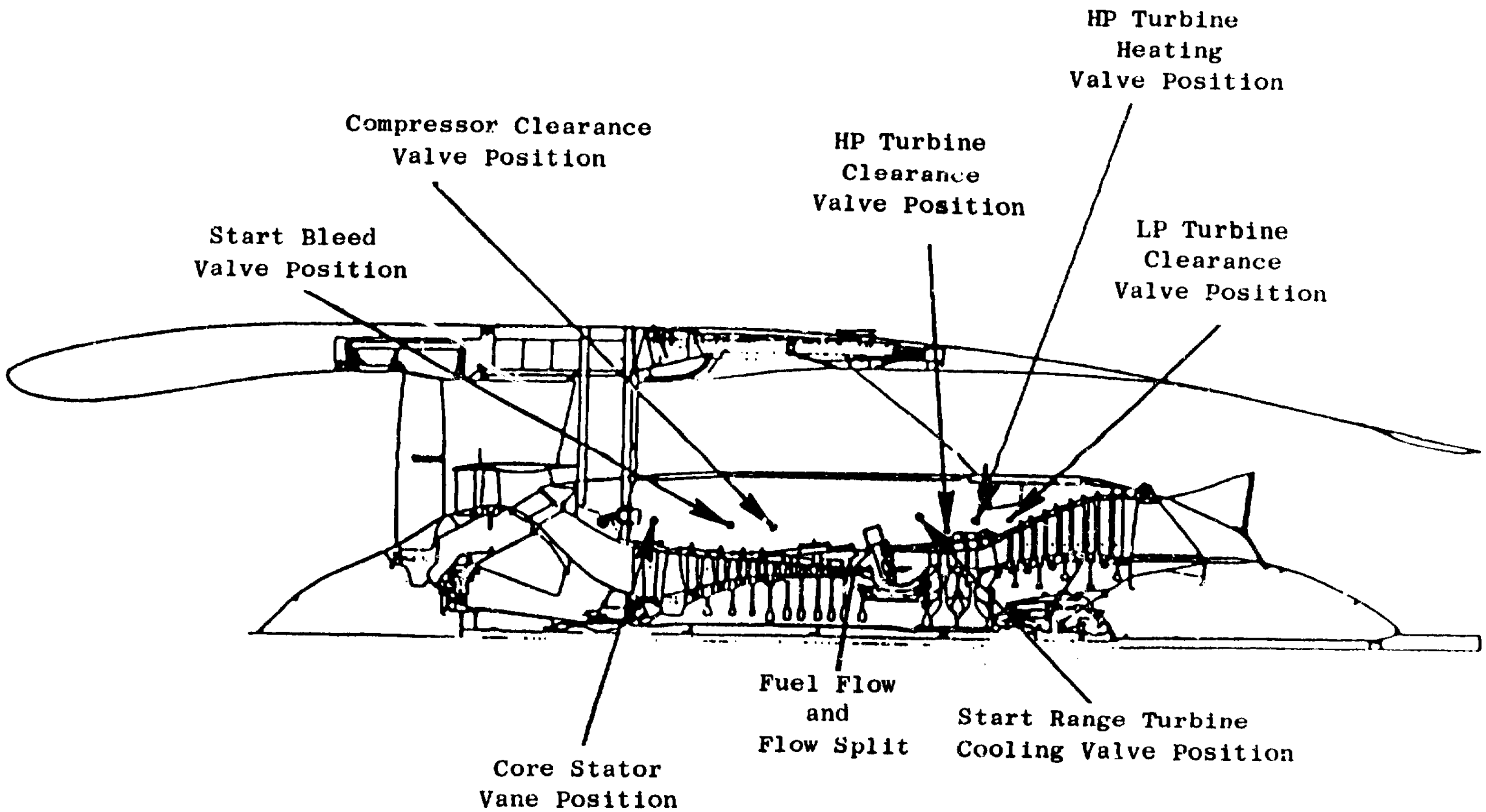

Figure 2. Control System Outputs.

4.0 BASIC SYSTEM STRUCTURE

Consideration of design requirements, particularly the one regarding digital electronic computation, led to the definition of a basic system structure as shown in Figure 3. The digital control is the central element in the system. It receives input signals from the control room and from various engine sensors, it provides servo signals to control the output devices shown, and it receives position feedback signals from the output devices.

Figure 4 shows pictorially the inputs that are received from outside of the control system. Seven temperatures are sensed including fan inlet air, compressor inlet and discharge air, HPT discharge gas, and engine skin temperatures in the three areas where active clearance control is provided.

Air pressure inputs to the system include freestream total pressure which is indicative of the average pressure at the fan inlet, compressor discharge pressure, and a total-to-static differential pressure from the customer bleed supply system. A pressure sensor is also provided for HPT discharge pressure which is a potential thrust control parameter. Current plans do not call for the use of this pressure on the demonstrator engines.

Inputs are also received that are indicative of fan rpm and core rpm, the latter being supplied from a core rotor-driven control alternator which also serves as the primary source of electrical power for the digital control. The control also receives 28 volt d.c. power from an external source for use during starts and as an alternate power supply in the event of an alternator failure.

Command data is provided to the digital control through a multiplexed digital link which simulates an aircraft interface connection. The primary command input is the position of the engine operator's power lever, but the data link is also used to transmit adjustments and selector switch positions from a control room Operator and Engineering Panel which provides experimental flexibility for demonstrator engine testing.

The data link also includes a separate channel for transmission of multiplexed digital engine and control system data to the control room, thereby

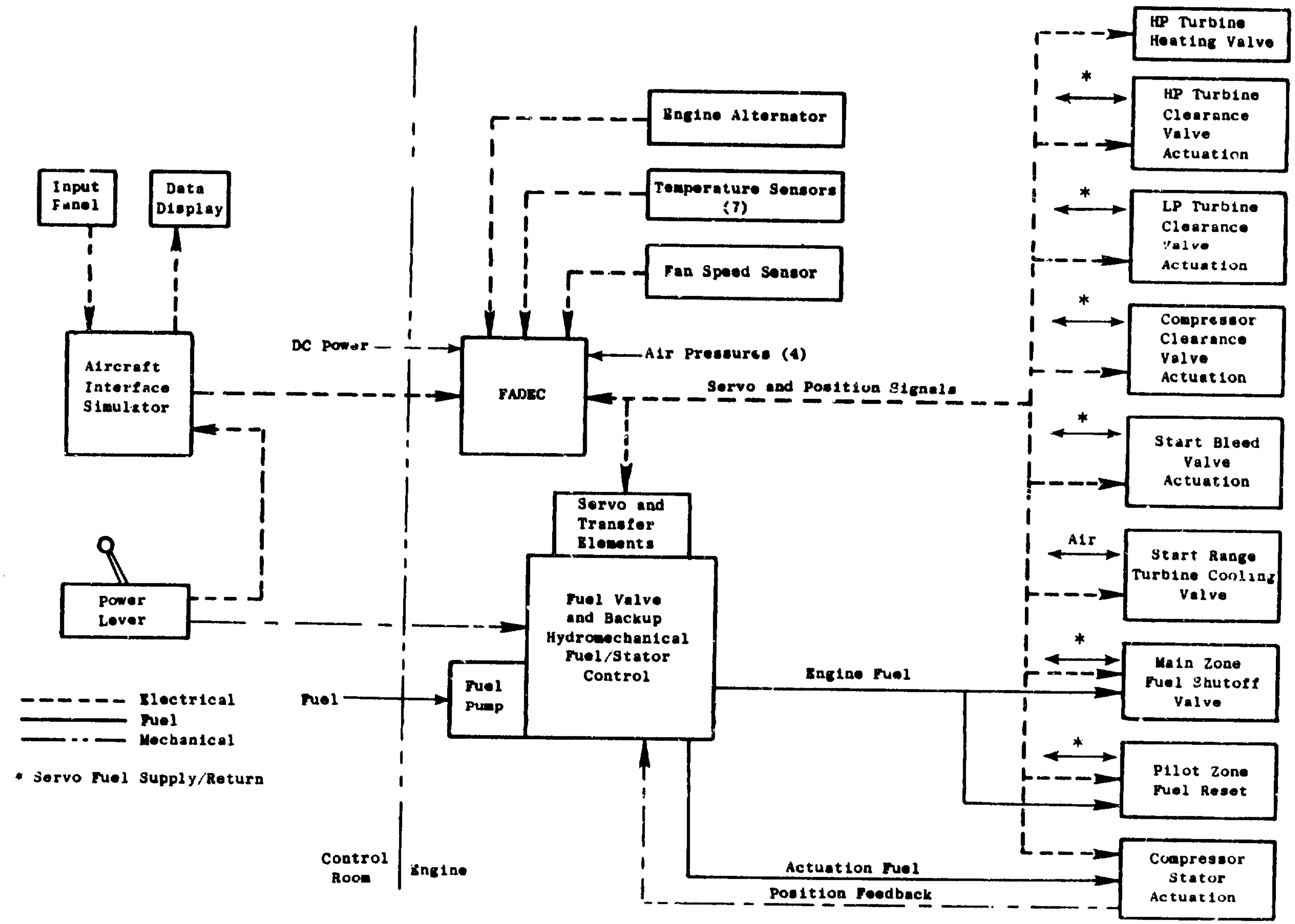

Figure 3. E^3 ICLS Control System.

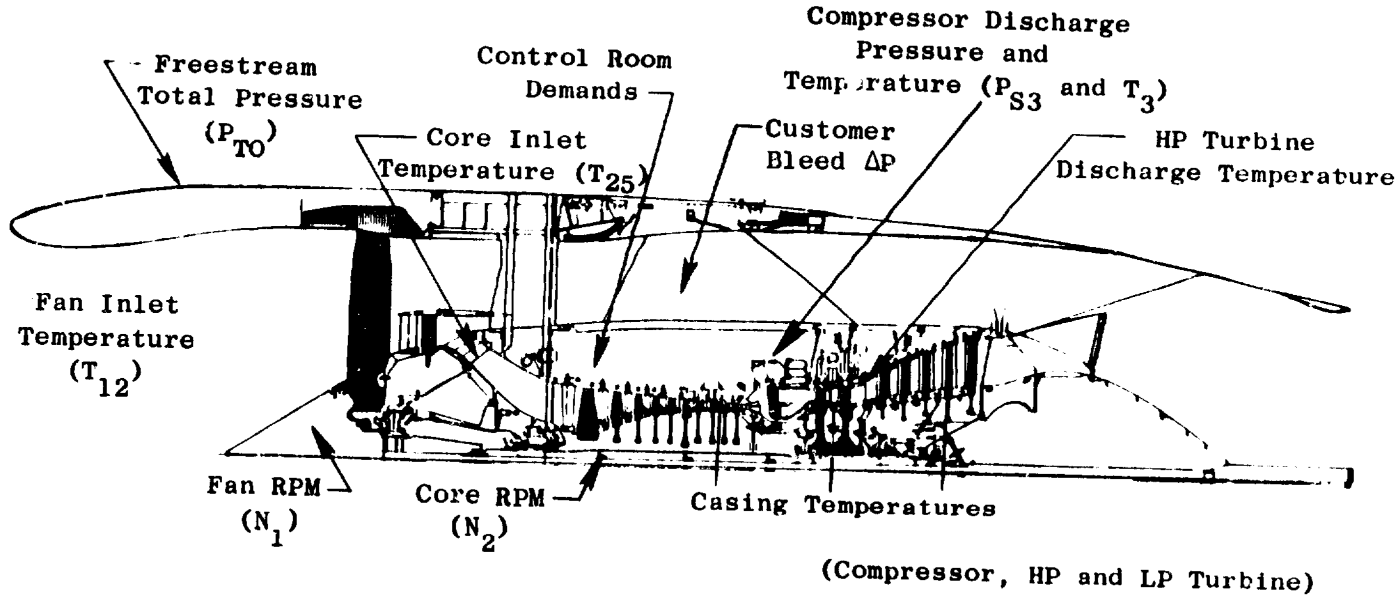

Figure 4. Control System Input.

simulating an aircraft engine monitoring connection. These data are displayed on a CRT and made available for the demonstrator engine test instrumentation system.

Control strategy for the various E^3 control system functions is contained in the digital control's program memory. Output signals are generated by the control and then transmitted to the various actuation devices in order to control them in accordance with the control strategy. Some of this control is done on an open-loop basis, but most is done closed loop by utilizing electrical position feedback signals from the actuation devices. Virtually all of the actuation is done with fuel-powered actuators using excess capacity from the engine fuel pump through electrohydraulic servovalves which respond to the digital control output signals. The only exceptions to this are the start range turbine cooling valves which are air-powered through a solenoid valve and the HPT heating valve which is a direct-acting solenoid valve.

Control outputs for the fuel valve and compressor stator actuators are handled differently from all others in that they are transmitted to transfer devices capable of providing switchover to hydromechanical control for these two variables only. In the event of a digital control system malfunction, fuel and stator control shifts to the hydromechanical backup plus all other controlled variables are set at safe positions so that the demonstrator engine will continue to run satisfactorily and can be shut down in a safe manner for correction of the malfunction.

Design details of system elements and system operation are given in the remaining sections of this report.

5.0 DELIVERY AND CONTROL OF FUEL FLOW

5.1 FUEL SYSTEM DESIGN

In designing the fuel system for the E^3, it was recognized at the outset that many of the considerations for establishing the highly successful fuel system designs on current transport engines, such as the CF6, are equally applicable to the E^3. Therefore, the E^3 system was patterned after the CF6 system in many ways, with modifications made mainly to reflect the use of a digital control and a significantly different combustor. A diagram of the fuel system design that resulted for the ICLS engine is shown on Figure 5.

An engine-driven, positive displacement vane pump with an integral centrifugal boost element is used in the system for pumping. Pump discharge fuel passes through a pump-mounted filter and into the fuel control mounted on the end of the pump.

In the fuel control, fuel metering is accomplished by the combined operation of the metering valve and a bypass valve that returns excess fuel to the inlet of the vane pump element. The bypass valve maintains a fixed differential pressure across the metering valve so that the metering valve area determines the amount of fuel flow supplied to the engine combustor. In the primary operating mode the metering valve is positioned by the digital control, and in the backup mode (discussed further in Section 10.1) it is positioned by the hydromechanical computer. A transducer on the metering valve provides position feedback to the digital control.

Metered fuel passes out of the fuel control through a pressurizing valve which is necessary to maintain sufficient pressure to operate fuel servos at low flow conditions and through a cutoff valve which provides a means for positively shutting off fuel to the engine. The fuel then passes through a flowmeter (which is included to provide experimental test data) and an engine lube oil cooler. Downstream from the cooler the fuel flow is split, part going to the pilot zone and part going to the main zone of the combustor. On/off valves in the main zone and pilot zone lines provide a means for modifying local fuel-air ratios in the combustor under certain conditions as explained below in the discussion on fuel flow split control.

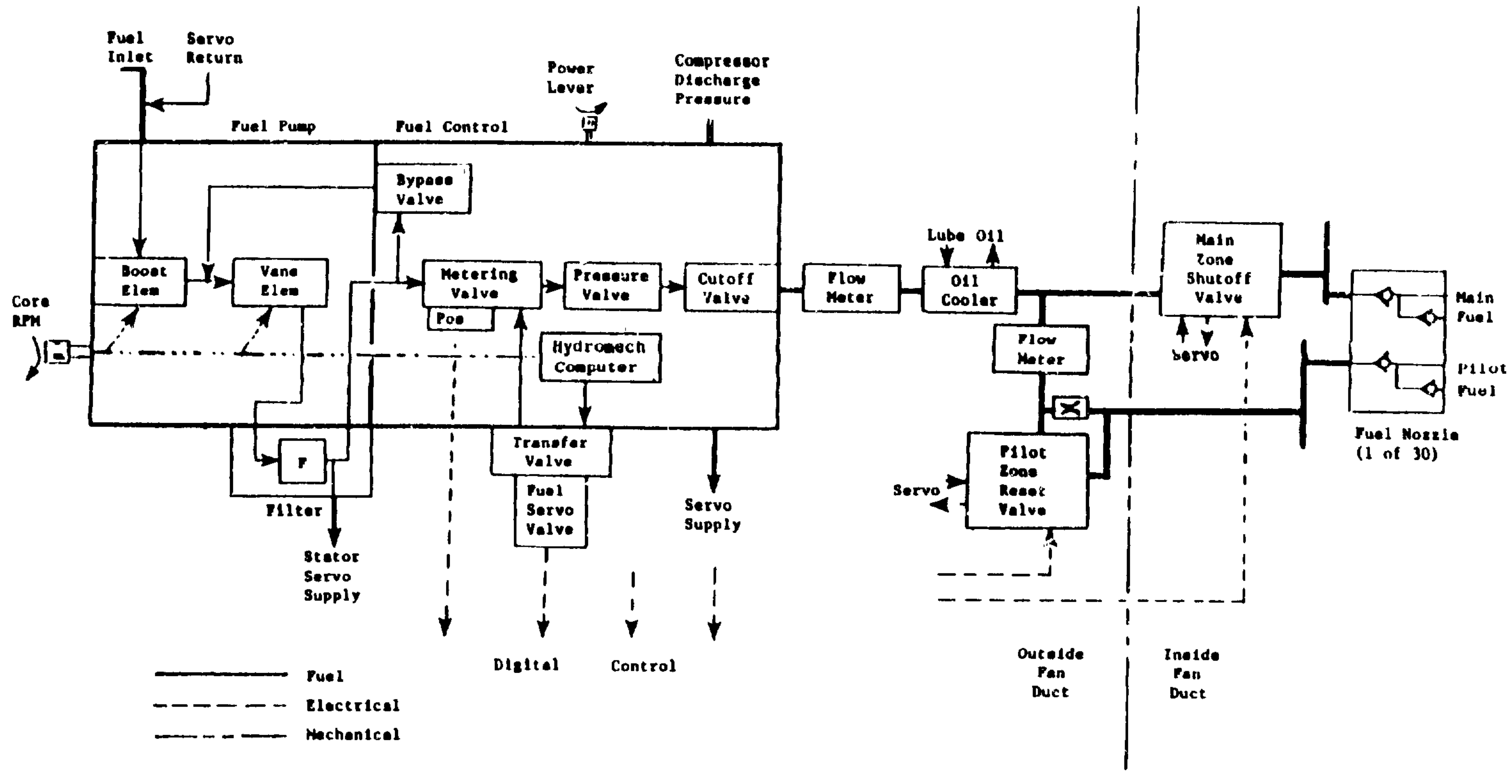

Figure 5. E^3 ICLS Fuel System.

5.2 FUEL CONTROL MODE STUDY

As one step toward defining the control strategy for fuel flow on the E^3, a control mode study was performed (Reference 1). The aim of the study was to determine the engine variable (or variables) that should be controlled by fuel flow in order to provide the best control of engine thrust in a large fleet of engines, considering the variations that will arise due to manufacturing tolerances, changing flight conditions, and wear. Consideration was also given to ease of sensing and suitability from a stability and response point of view.

The study was begun by establishing a list of potential fuel control variables which would indicate net thrust at any flight condition as a percentage of the maximum rated thrust at that condition (i.e., a thrust parameter). A candidate thrust parameter should be suitable for use in cockpit indication and should correlate with percent-net-available thrust independent of customer air bleed, control errors, engine component variations, and flight conditions.

A list of the thrust parameters considered is shown in Table I. Eleven of these thrust parameters are of the conventional type that utilize a single sensed variable and a schedule for this variable. The other three (TP10, TP11, and TP12) are dual thrust parameters which utilize two variables to provide some discrimination between control variations that can be ignored and those component variations that cannot be ignored in setting power. Earlier studies have indicated that such dual thrust parameters have the potential for reducing the effects of engine-to-engine variations, thereby reducing the amount of temperature margins that must be designed into engine hot parts to account for these variations.

A key factor in setting up the control mode analysis was the definition of tolerances for the independent variables; that is, for the controlled variables in each mode being studied and for basic engine component characteristics.

Controlled variable tolerance estimates were begun by estimating sensing tolerances. Current state-of-the-art sensors were assumed with full-scale

Table I. Mode Analysis Thrust Parameters and Controlled Variable Tolerances, Percent of Point.

Thrust Parameter	Sea Level Takeoff Error	Max Climb (MXCL) Error Mach 0.632/ 4.57 km (15K)
TP1 - LP Turbine EPR (P49/PTO)	±1.60%	±2.30%
TP2 - HP Turbine EPR (PS3/PTO)	1.50	2.30
TP3 - $P8/P_{amb}$	1.50	2.30
TP4 - PS15/PTO	1.50	2.30
TP5 - M11	1.70	2.40
TP6 - T41/T1	1.00	1.00
TP7 - Corrected Core Speed (PCNHR)	0.25	0.25
TP8 - Corrected Fan Speed (PCNLR)	0.25	0.25
TP9 - T49/T1	1.00	1.00
TP10 - f(PCNLR, T49)	0.25, 1.00	0.25, 1.00
TP11 - f(PCNLR, T41)	0.25, 1.00	0.25, 1.00
TP12 - f(PCNLR, EPR)	0.25, 1.60	0.25, 2.30
TP13 - WFE/PTO	1.00	1.00
TP14 - P8/PTO	1.50	2.30

ranges set based on the E^3 cycle and flight envelope. Tolerance distributions were optimized, whenever possible, for certain scale ranges based on engine needs.

The tolerance assignments also included analog-to-digital (A-D) conversion errors and estimated sampling errors based on the uncontrolled effects of local flow distortions. Scheduling errors were estimated where secondary or trim parameters were used to define operating values for the control variables. Errors due to sampling, sensors, signal conditions, and A-D conversion were combined by the root-sum-square method. All of the above factors were combined to give the controlled variable tolerances shown in Table I.

There are noncontrol factors that influence engine performance to a varying degree depending on the mode of control. These include engine component variation due to manufacturing tolerances and service wear and also include engine bleed and power extraction as required for anti-icing and aircraft accessories. Table II lists the values used in the mode study.

The actual mode analysis is accomplished by using a computer deck representing the E^3 cycle under steady-state conditions. A special routine is used with this deck to generate matrices of partial derivatives of certain dependent variables with respect to certain other independent variables. Among the independent variables were potential control variables, air bleeds, power extraction, and engine component performance variables which contribute significantly to overall propulsion system performance. The dependent variables included such key cycle variables as thrust, sfc, temperatures, stall margins, and rotor speeds.

The mode analysis consisted of a series of computer runs using the matrices of these partial differentials. For each run a different control variable was designated and a matrix was used that had this as its independent variable. Predicted tolerances for sensors, controls, and engine components were multiplied by the appropriate partial differentials. These effects on the key dependent variables based on the square root of the sum of the squares (RSS) were accumulated. Deterioration factors determined from actual field experience were applied to the partials, and the accumulation of these factors was established.

Table II. Mode Analysis Engine Component Variations, Percent of Point.

Variable	Variation	Deterioration
Fan Corrected Flow	±0.5%	-0.5%
Fan Efficiency	1.0	-0.4
Core Compressor Corrected Flow	0.5	0
Core Compressor Efficiency	1.0	-0.6
Burner Pressure Loss (P4/P3)	0.5	0
HP Turbine Area Corrected Flow	1.0	0
HP Turbine Efficiency	1.0	-1.5
LP Turbine Area Corrected Flow	1.0	0
LP Turbine Efficiency	0.5	-1.0
Fan Duct Pressure Loss	0.2	0
Postturbine Core Pressure Loss	0.2	0
Compressor Interstage Bleed (% of W25)	1.0	0
Compressor Discharge Bleed (% of W25)	1.0	0
Shaft Power Extraction (Horsepower)	25.0	0
Core Engine Jet Nozzle Area (A8)	0.5	0
Bypass Duct Discharge Area (AE16)	2.0	0
Nozzle Flow Coefficient (CF8)	0.5	0

The results of the computer runs for the single-parameter modes are tabulated in Table III in terms of thrust variations caused by tolerance effects on new engines and deterioration effects. The modes are rated in order of increasing thrust variations. The four best modes were run at other flight conditions with results as shown in Table IV.

Typical results for the dual-parameter modes are shown in Figures 6, 7, and 8 which relate to TP11. Figure 6 shows the statistical variations in thrust and T41 resulting from new engine tolerances and deterioration effects if only half of TP11 is utilized (that is, $N1/\sqrt{\theta 12}$). In order to meet the minimum thrust guarantee with all engines, it is necessary to set the thrust parameter higher. This shifts the envelope of Figure 6 along the $\Delta Fn/\Delta T41$ slope for an N1 increase resulting in the envelope shown on Figure 7 where the maximum T41 is 311 K (99° F) higher than the original design nominal.

The basic idea behind the dual thrust parameter is that some hot engines tend to be high-thrust engines (shown in Figures 6 and 7). Thus, it should be possible to trade some thrust for some temperature and meet thrust guarantees with less temperature spread throughout a large group of engines. This would be implemented as shown in Figure 8 with the trim schedule designed to bring all of the below average thrust engines on Figure 6 up to at least the average engine thrust level. The net effect of this would be to limit the maximum T41 (the hottest deteriorated engine) to 305 K (89° F), 6 K cooler than without the dual-parameter trim effect.

Results with the other dual parameters were similar to TP11. Thus, the benefits of the dual-parameter approach are small on the E^3; since the is some concern over the stability aspects of this approach, it was not pursued further. On future, more complex engines the dual-parameters approach might prove worthwhile.

As a final step in the mode analysis, several thrust parameters were evaluated relative to the effects of increasing aircraft velocity during takeoff (takeoff thrust lapse). Of particular interest were net thrust and T41 for a fixed power lever setting with each mode.

Figure 9 shows the results of the thrust lapse analysis. The analysis showed the expected loss of net thrust with increasing aircraft speed. It

Table III. Mode Analysis Results at Takeoff and Maximum Climb.

Thrust Parameter		Sea Level Static Takeoff			Max. Climb (MXCL) Mach 0.632/ 4.57 km (15,000 FT)		
		FT	FD	Rank	FT	FD	Rank
TP1	P49/PTO	±2.04%	+0.06%	3	±3.75%	+0.46%	3
TP2	PS3/PTO	±2.43	+0.43	4	±4.28	+0.98	4
TP3	$P8/P_{amb}$	±4.20	+0.025	7	±7.21	+0.51	9
TP4	PS15/PTO	±5.26	-0.39	8	±6.72	+0.10	6
TP5	XM2A	±2.74	+0.77	5	±7.14	+1.97	10
TP6	T41/T1	±3.79	-4.63	9	±4.84	-5.73	7
TP7	$N2/\sqrt{\theta 25}$	±2.73	+1.81	6	±3.78	+2.84	5
TP8	$N1/\sqrt{\theta 12}$	±0.785	-0.135	1	±1.73	+0.10	1
TP9	T49/T1	±4.33	-6.12	10	±5.53	-7.74	8
TP13	WFE/PTO	±1.25	-1.98	2	±1.45	-2.26	2
TP14	P8/PTO	±4.20	+0.025	7	±7.21	+0.51	9

FT = Thrust Variation Due to Tolerances Effects

FD = Thrust Variation Due to Deterioration Effects

Table IV. Mode Analysis Results at Other Flight Conditions.

Flight Condition Mode	2 Max. Cruise (MXCR) Mach 0.81 10.67 km (35,000 ft) FT	FD	4 SLS 90% FT	FD	5 SLS 75% FT	FD	6 SLS 50% FT	FD	7 SLS Flight Idle FT	FD	8 SLS Ground Idle FT	FD
TP8	±1.64%	0.27%	±0.82%	-0.15%	±0.79%	-0.15%	±0.90%	-0.26%	±0.81%	-0.29%	±0.74%	-0.22%
TP13	±1.18	-1.66	±1.34	-2.16	± .48	-2.47	±1.73	-3.00	±5.05	-7.84	±7.30	-8.50
TP1	±3.38	0.54	±2.14	0.16	±3.06	0	±3.52	-0.06	±31.39	-0.19	±65.37	-0.33
TP2	±3.90	1.06	±2.54	0.46	±3.42	0.46	±3.69	0.47	±15.65	0.54	±19.86	0.15
FN kg(lb)	3823.0 (8428.0)		14,896.0 (32,839.6)		12,417.0 (27,375.0)		8278.0 (18,249.6)		1655 (3650.0)		662 (1460.0)	

FT = Thrust Variation Due to Tolerance Effects

FD = Thrust Variation Due to Deterioration Effects

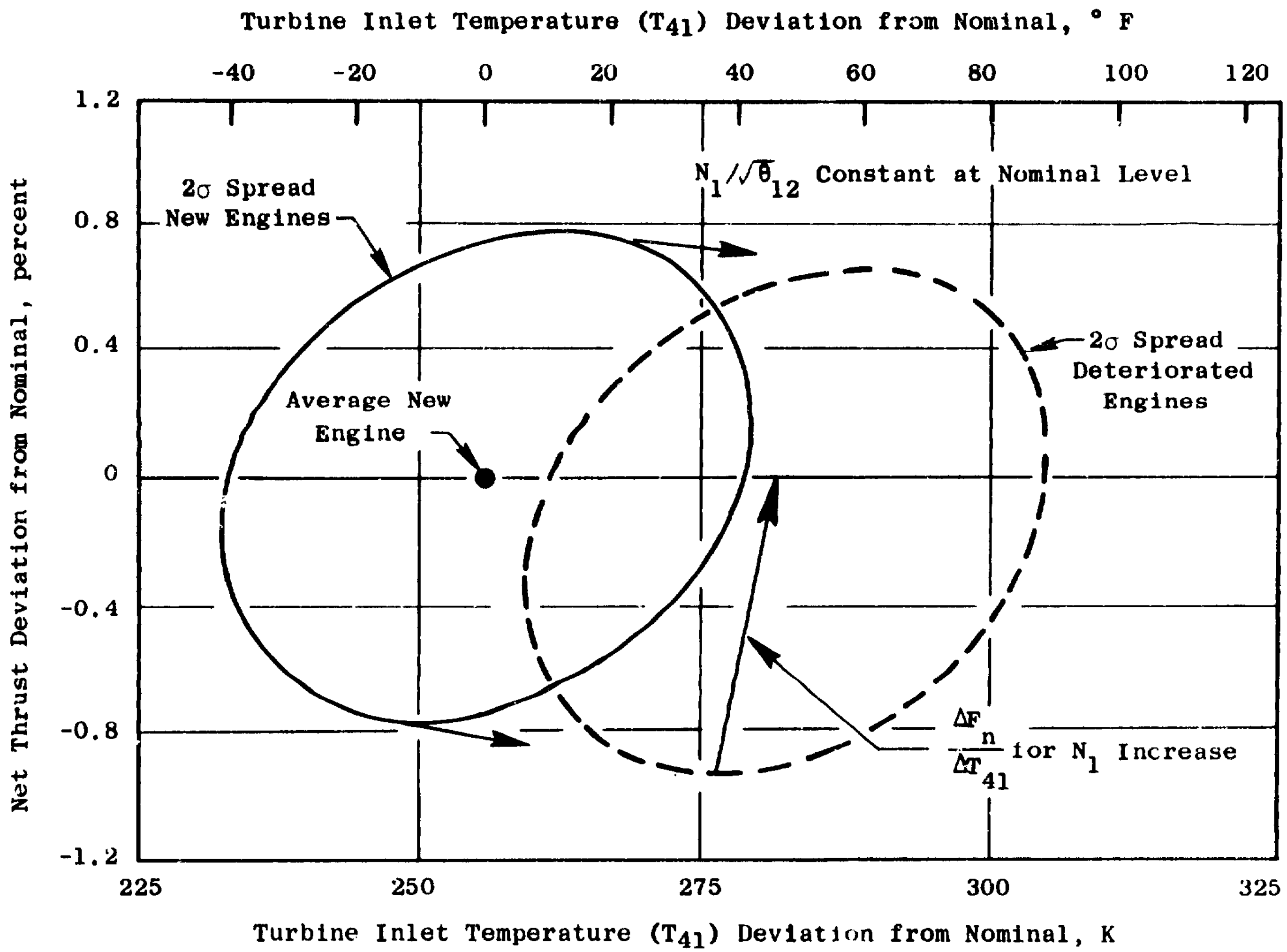

Figure 6. E^3 Thrust/Temperature Variations.

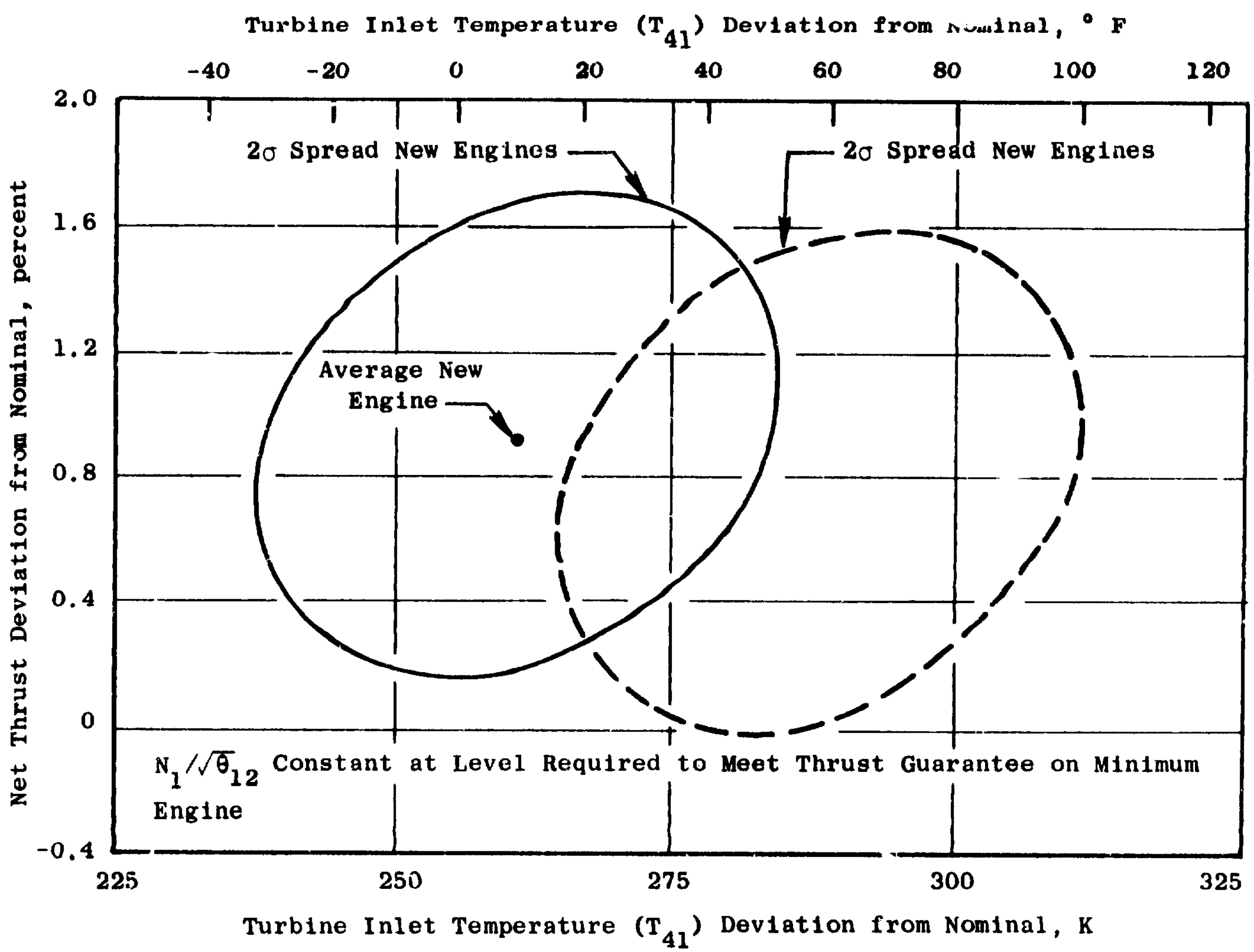

Figure 7. E^3 Thrust/Temperature Variations.

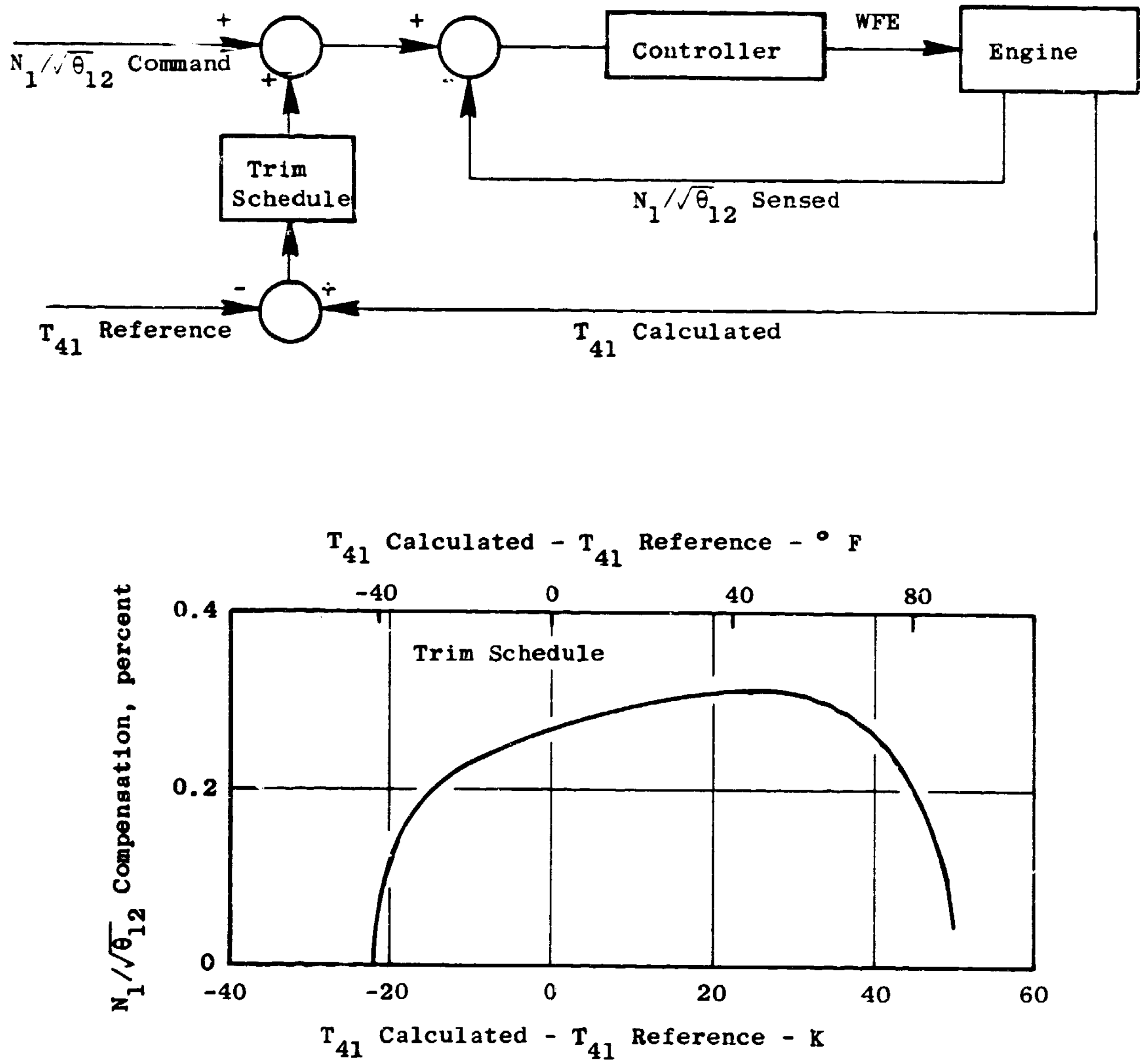

Figure 8. Dual Thrust Parameter Implementation.

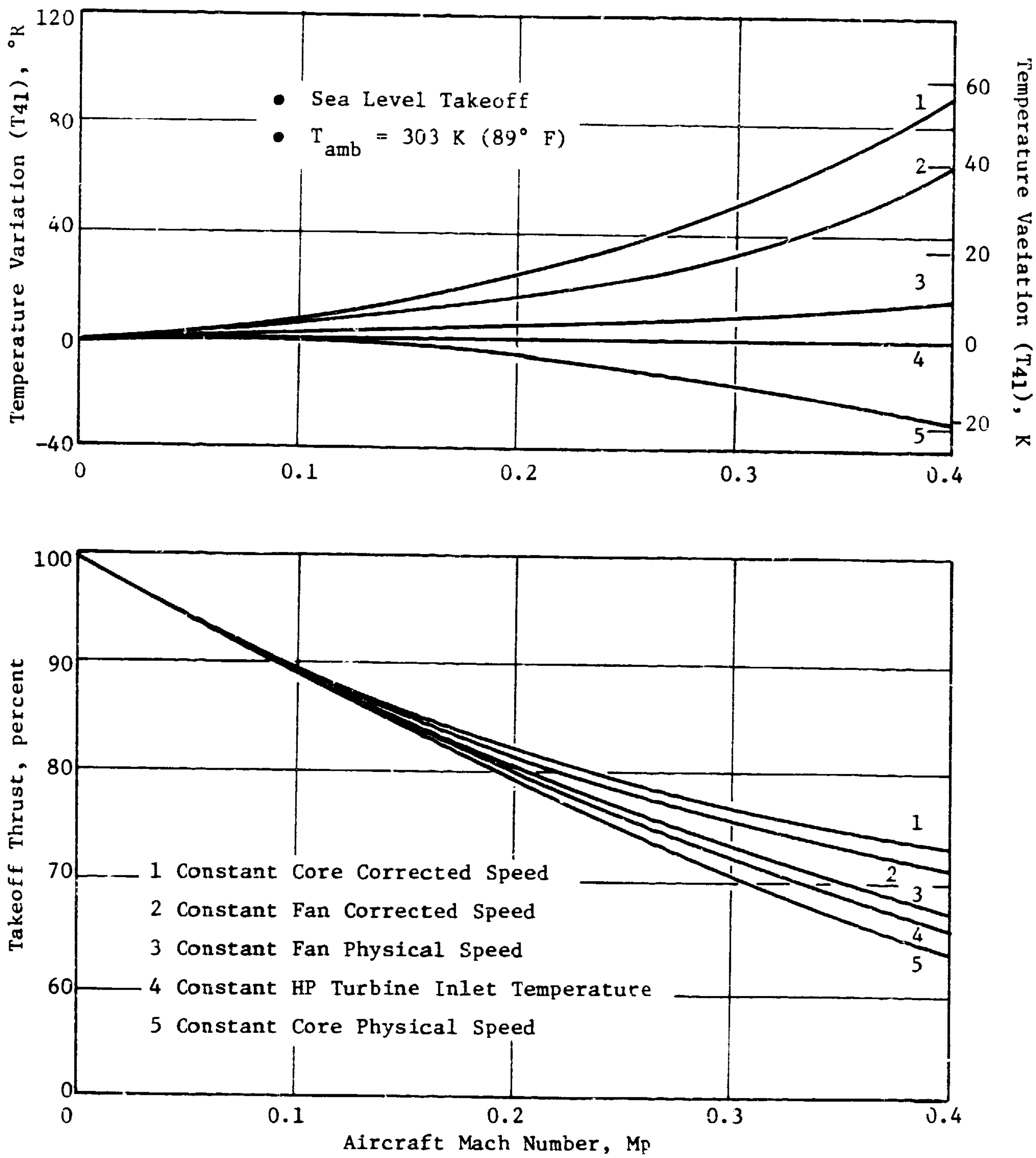

Figure 9. Thrust Lapse Rate Analysis.

also shows that the selected control mode directly affects the thrust level. Constant corrected core speed provides maximum thrust for the modes examined, but also shows the greatest increase in HP turbine inlet temperature. Constant real core speed results in the lowest net thrust and minimum temperature at the HPT inlet. These results show the expected correlation of temperature and thrust in the engine.

Since it is desirable to minimize the temperature increase for this operation, an approach which would maintain constant HPT inlet temperature is most desirable. The single parameter mode analysis results indicated that constant corrected fan speed produces minimum thrust variations due to quality and deterioration. It appears that corrected fan speed with an aircraft Mach number or PTO trim should be used.

The final conclusion of the control mode analysis was that TP8, corrected fan speed, is the most desirable thrust parameter for E^3. That is, a fuel control strategy using fuel flow manipulation to control corrected fan speed will provide the minimum variation in thrust due to engine tolerances and deterioration at key operating conditions. The analysis further indicated that an aircraft Mach number or PTO trim should be applied to the basic fan corrected speed schedule to provide compensation for takeoff thrust lapse.

5.3 FUEL CONTROL STRATEGY

Having selected corrected fan speed as the basic fuel control parameter, definition of the complete control strategy for fuel flow proceeded, and the strategy shown in block diagram form in Figure 10 was established.

Fuel flow, for the most part, is modulated to control fan or core rotor speed in accordance with the power lever angle (PLA) schedules shown as blocks in the center and lower left portion of the diagram. For ICLS, the schedules are set up so that the core speed schedule is in effect from idle to approximately 30% thrust and the fan speed schedule is in effect above that, providing power management as a function of ambient pressure (P0), fan inlet temperature (T12), and Mach number (Mp).

Limits are imposed on the basic schedules to prevent excessive HPT inlet temperature (calculated), excessive LPT inlet temperature (T42), and excessive

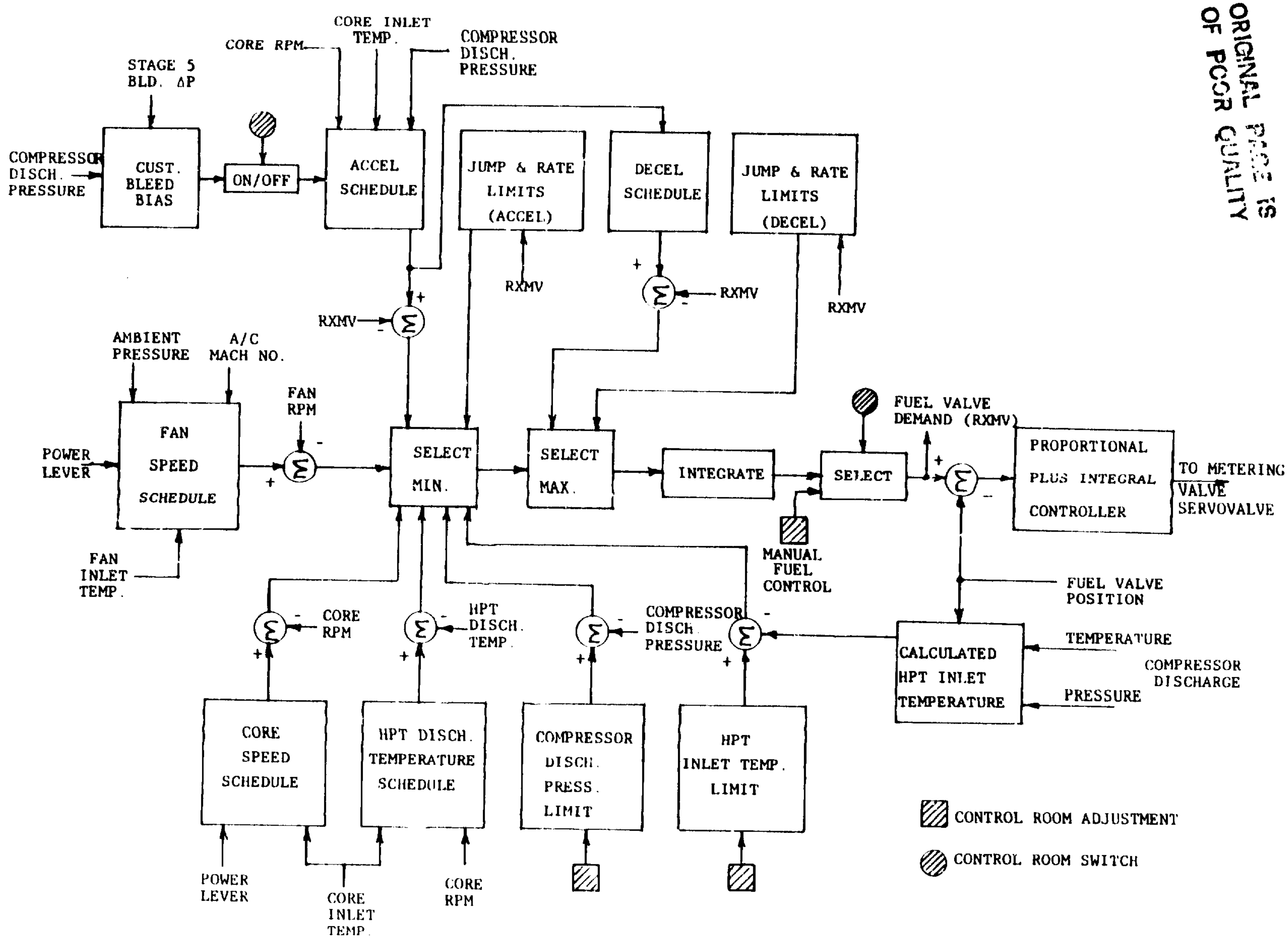

Figure 10. ICLS Fuel Control Strategy.

compressor discharge pressure (PS3). In addition, transient fuel schedules and limits are included to (1) prevent compressor surge during rotor accelerations, (2) prevent loss of combustion during rotor decelerations, and (3) limit thermal shocks (by limiting fuel flow rate-of-change). The schedules and limits are combined in a selection network which establishes priorities and assures smooth transition between control modes. A manual input is included to provide the capability of adjusting fuel flow from a control room potentiometer to explore subidle engine characteristics.

The control will have the capability of sensing customer bleed airflow from the compressor and applying appropriate compensation to the acceleration fuel schedule. For the core and ICLS this will be an optional function which can be deactivated by means of a control room switch.

The output of the selection network is a fuel metering valve position demand that operates a position control loop to position the valve, thereby setting the desired fuel flow.

5.4 FUEL FLOW-SPLIT CONTROL STRATEGY

The E^3 double-annular combustor shown in cross section in Figure 11 requires that fuel from the main fuel metering valve be split between the pilot and main zones. The required flow-split characteristics are listed below.

Start Mode - Full fuel flow is required to the pilot zone to assure ignition and best combustion during acceleration to idle.

Alternate Start Mode - If high compressor bleed flow is required for starting, acceleration to idle with pilot flow only may create an intolerable turbine inlet temperature level and profile combination. To cover this condition an alternate control mode is required that provides pilot fuel only for ignition, temporary pilot leaning after ignition to get main zone ignition, and a uniform split after main zone ignition for best temperature profile during accel to idle.

Run Mode - Full fuel flow to the pilot zone is required at idle when not in flight to provide minimum exhaust emissions. Above idle or in flight, fuel is required to both zones.

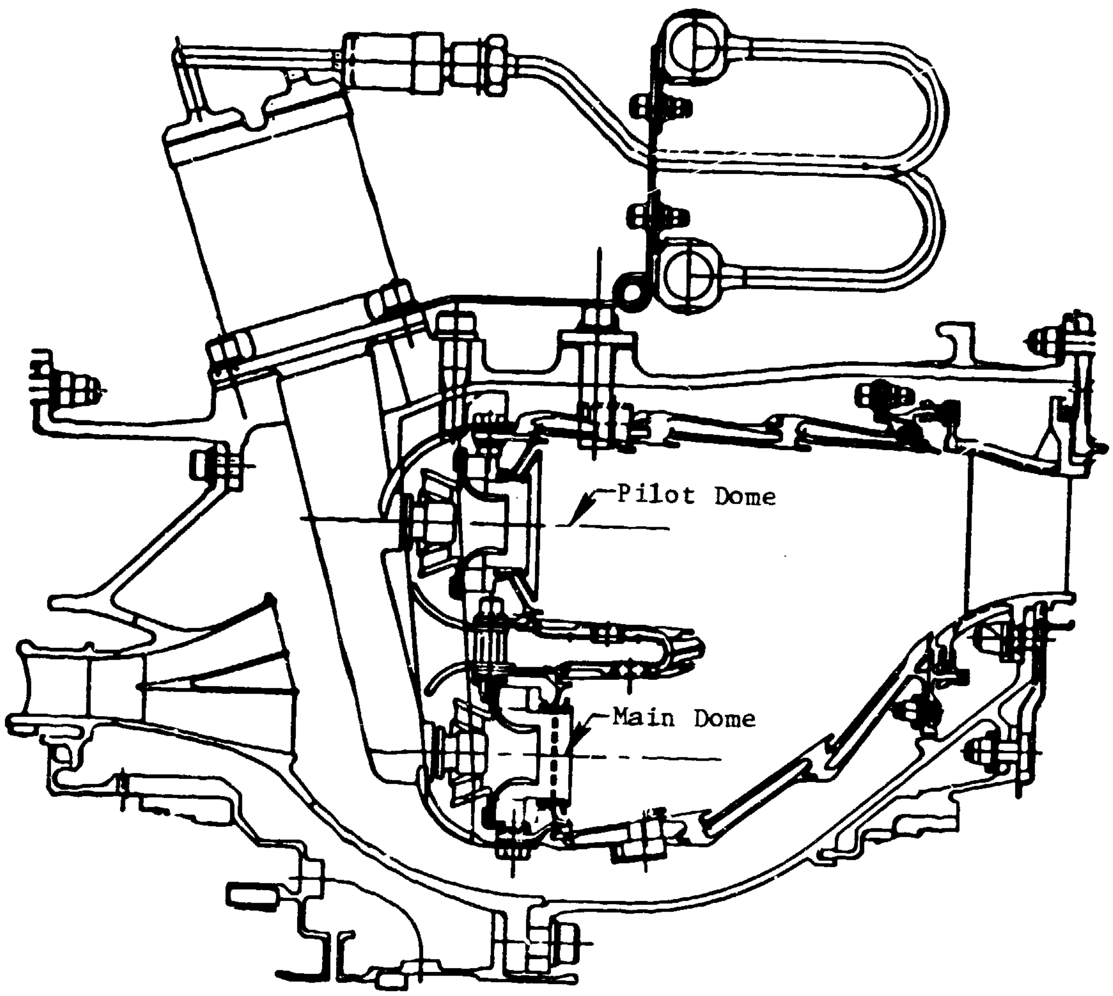

Figure 11. E^3 Double-Annular Combustion.

Decel Mode - Temporary switchover to pilot-zone-only flow during rapid deceleration is required as an experimental option for use only if decel blowout problems are encountered.

Transition - For transition to full burning mode, main zone flow must be temporarily held low to prevent pilot starvation as main injectors fill.

The control strategy designed to meet these requirements is shown on Figure 12. The block at the upper left provides the basic on/off logic for the main zone shutoff valve, including the alternate start mode logic, and the blocks at the bottom provide the pilot zone reset that is a part of this alternate mode. The blocks in the center provide the main zone throttling function to prevent pilot zone starvation during transition to full burning. The duration of throttling is varied as a function of total fuel flow as indicated by main fuel metering valve position and as a function of the time since last main zone operation.

The decel mode logic is shown in the block at left center. An adjustment on the deceleration rate required to trigger this mode is provided so that this function can be modified or deleted altogether from the control room during engine operation.

A manual mode is also provided for both the main zone shutoff valve and the pilot zone reset valve which allow each valve to be independently positioned from the control room during engine operation.

The output of the main zone shutoff logic network operates the main zone valve through a control loop that includes position feedback so that the valve can be set at any position from fully closed to fully open. The pilot zone reset valve servocontrol does not include position feedback so this valve can only be set fully open or fully closed.

5.5 FUEL CONTROL LOOP DETAILED DESIGN

Design details of the fuel control strategies just described were defined primarily on the basis of predicted engine cycle characteristics using data from the computer model of the engine at steady state (cycle deck) and data from transient computer models derived from the steady-state model.

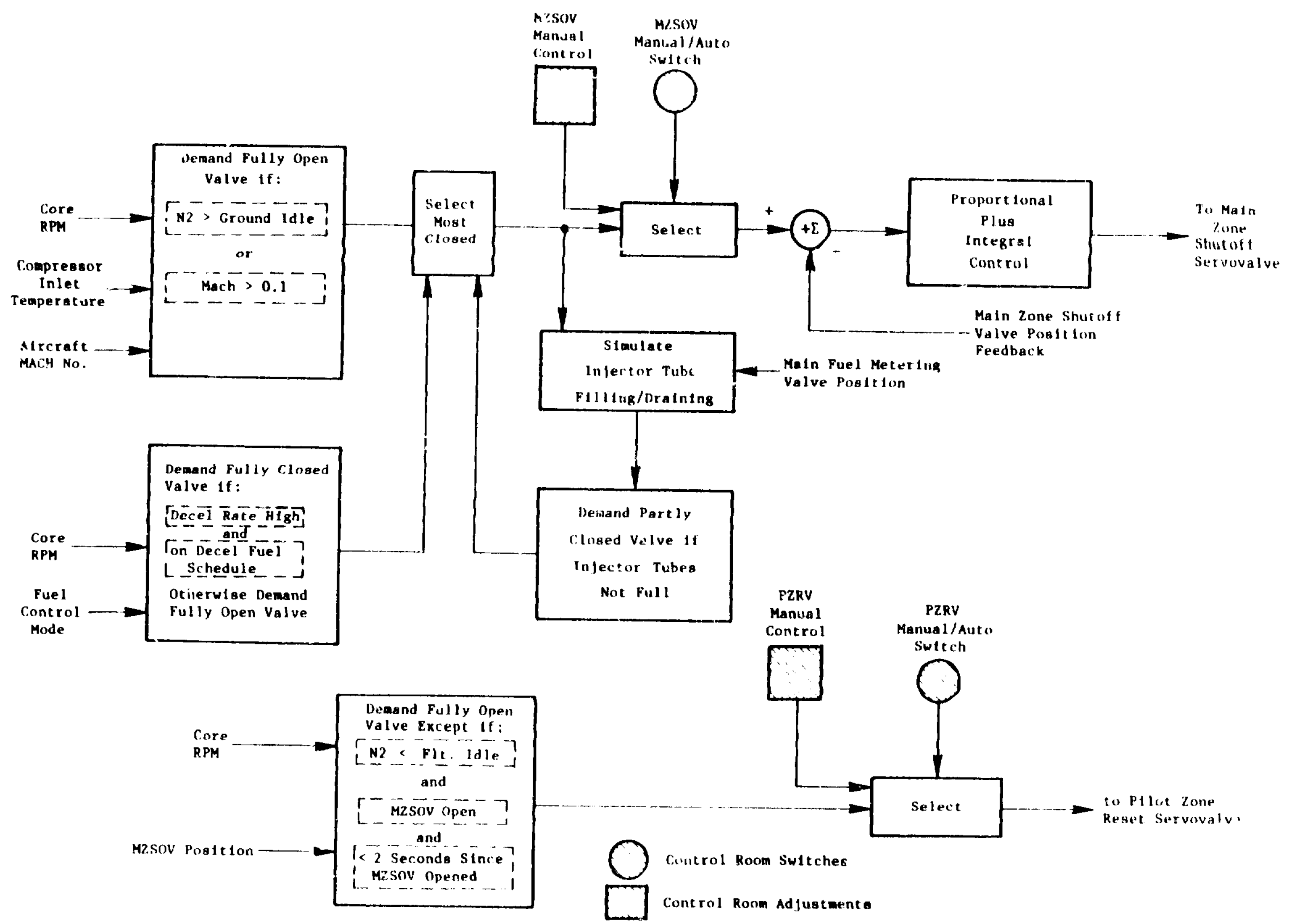

Figure 12. Fuel Flow Split Control Strategy.

The basic fuel control system schedules of core and fan rpm as functions of power lever angle were designed so that the relationship between angle and thrust is nearly linear at ICLS operating conditions. The schedules, shown on Figures 13 and 14, are designed so that the corrected fan rpm schedule is normally in effect above approximately 70° power lever and the corrected core rpm schedule is in effect below.

The dynamic characteristics of the fuel control loop were designed by the use of linear stability analysis techniques and by the use of a transient model of the engine and control on a hybrid computer.

The transient engine model was based on the E^3 steady-state cycle deck with component subroutines programmed directly from the cycle deck source. The block diagram in Figure 15 shows the information flow through the model. The diagram consists of blocks connected by flowpath techniques. These blocks represent the component subroutines just noted. Each block is identified by the engine-component thermodynamic function represented therein. Inputs to the engine components on each pass include flight conditions, iteration variables from the iteration logic, rotor speeds from the rotor simulations, and control variables from the control simulation. Compressor bleed and horsepower extraction are not shown but are included. Separate blocks represent inputs and outputs for the iteration logic, rotor simulations, and control simulation.

The stability analysis effort and the transient model work resulted in control system dynamic characteristics that produce the engine transient characteristics shown in Figure 16 which is a set of data traces showing a fast deceleration followed by a fast acceleration on the transient model.

The dynamic design work just described was limited to the region above idle because the engine cycle deck and transient model are limited to that region. Therefore, a separate subidle engine model was prepared to aid in designing the transient characteristics in the starting region. This model was patterned after a similar subidle model for an existing engine and adjusted to match predicted E^3 characteristics at idle. It was further adjusted when actual subidle data became available from component testing of the compressor and HP turbine.

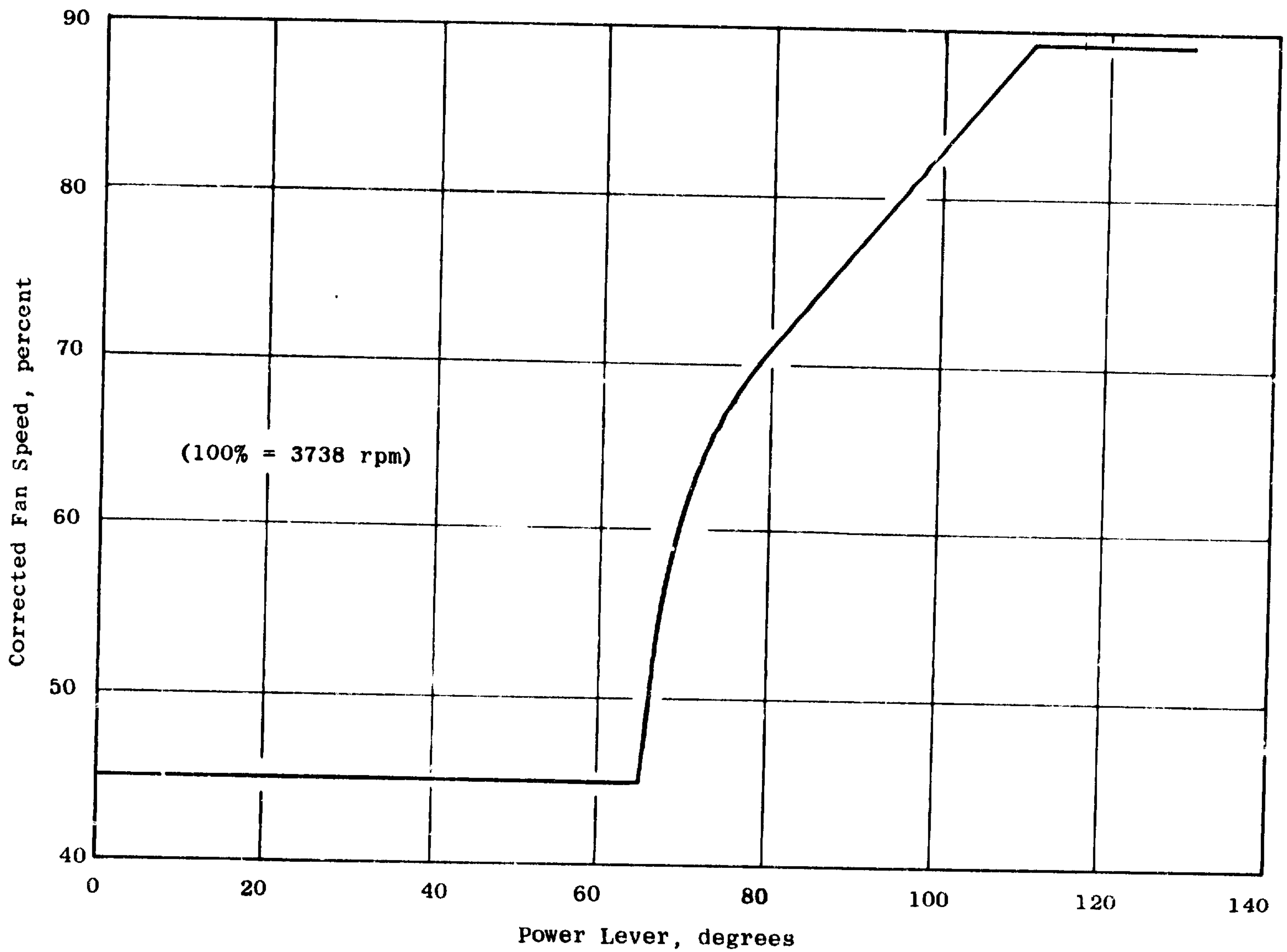

Figure 13. Power Lever Schedule of Corrected Fan Speed.

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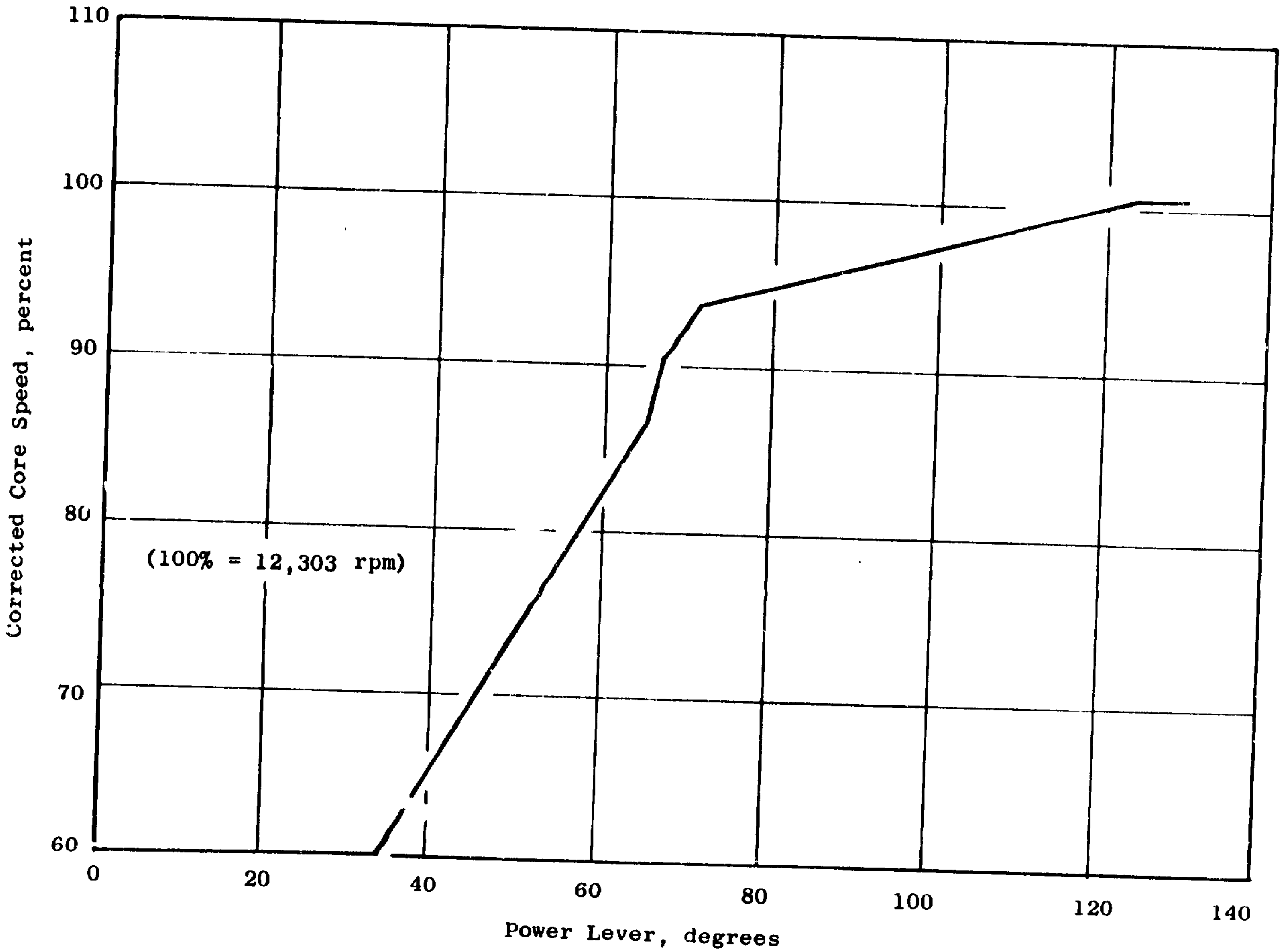

Figure 14. Power Lever Schedule of Corrected Core Speed

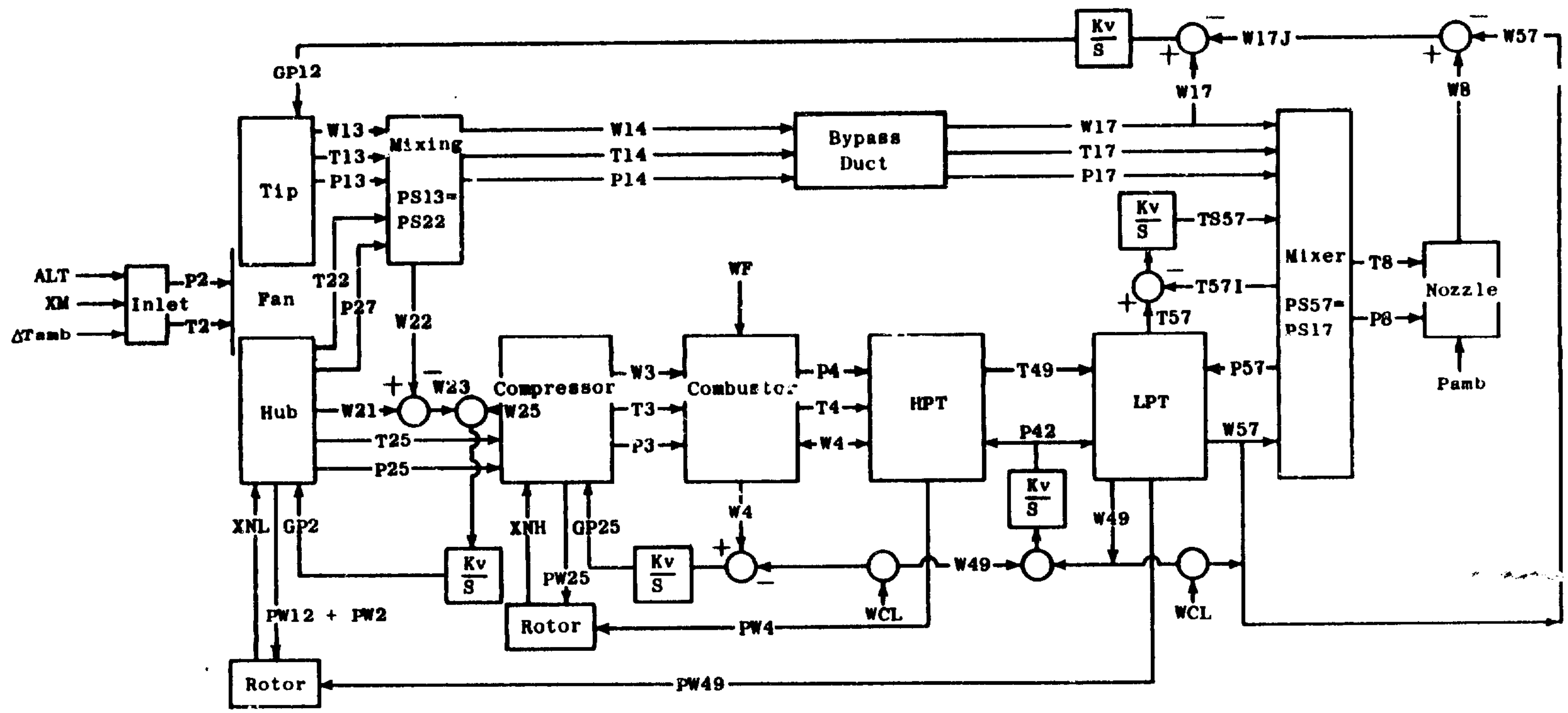

Figure 15. E^3 Hybrid Model Block Diagram.

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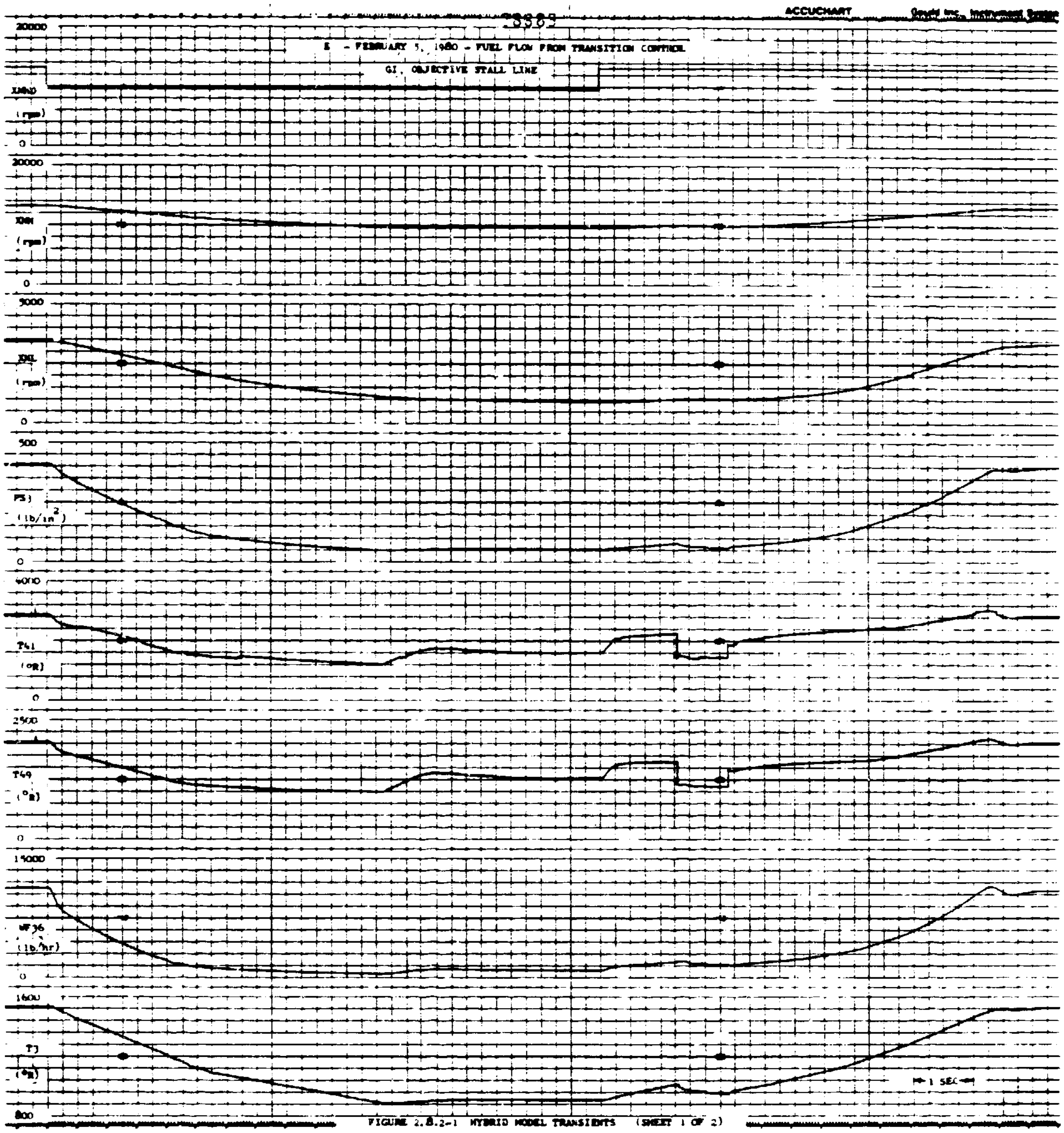

Figure 16. Hybrid Model Transients.

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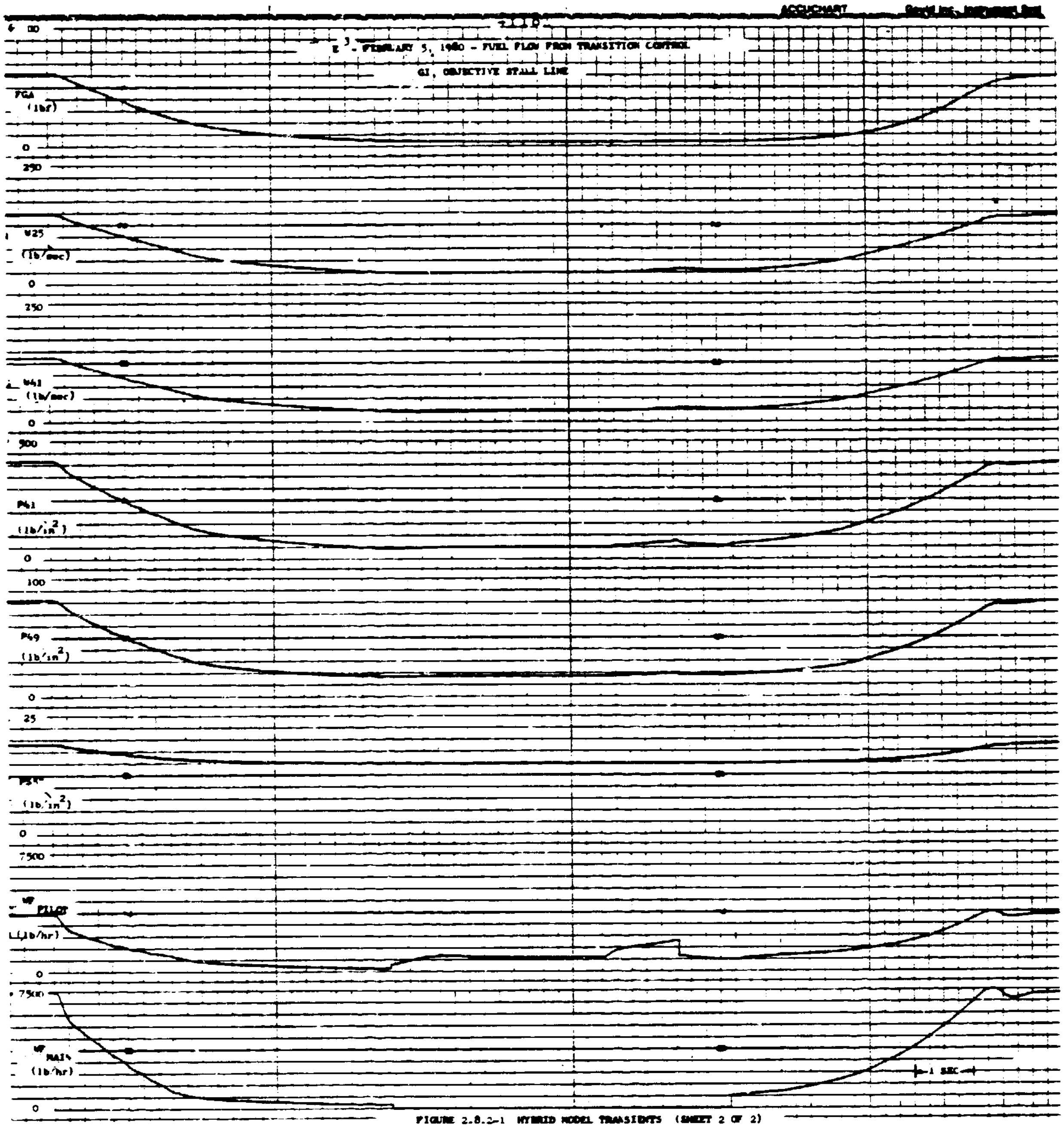

Figure 16. Hybrid Model Transients (Concluded).

Figures 17 and 18 show typical subidle model data pertinent to control of fuel flow and to choice of a starter. Design objectives call for a 60-second start on a standard day, while maintaining at least 10% compressor stall margin and limiting turbine inlet temperature to 1228 K (1750° F) maximum. A preliminary fuel schedule meeting the latter two criteria is plotted on Figure 17 and the resulting core rotor torque characteristic is shown in Figure 18.

Work with the subidle model is not complete as this report is written because additional component test data remains to be obtained. However, based on early subidle model results, the E^3 has been designed to use two Hamilton Standard PS600-3 air turbine starters, the largest readily available starters of this type, in order to assure meeting the 60-second start-time goal.

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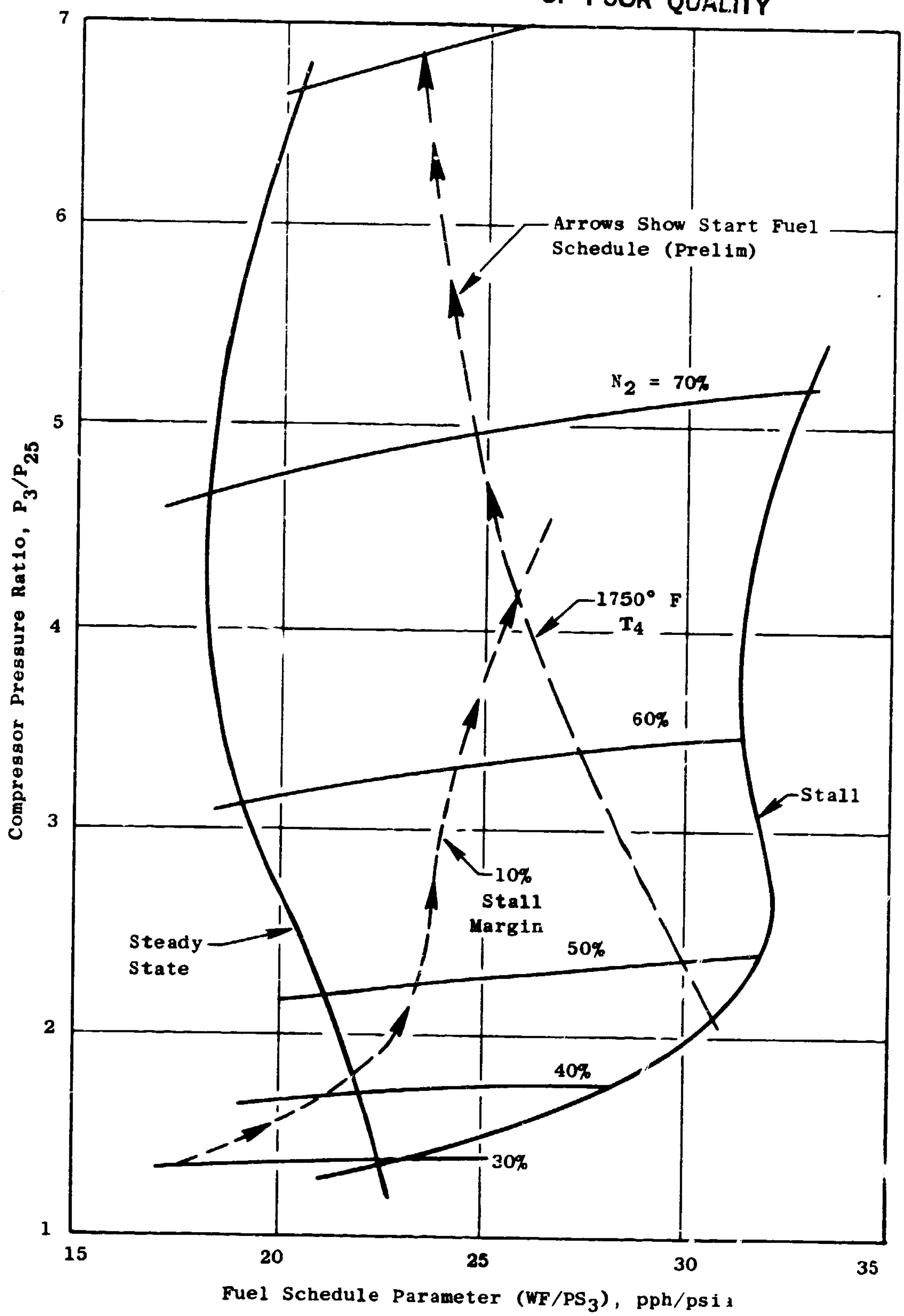

Figure 17. Subidle Model Data.

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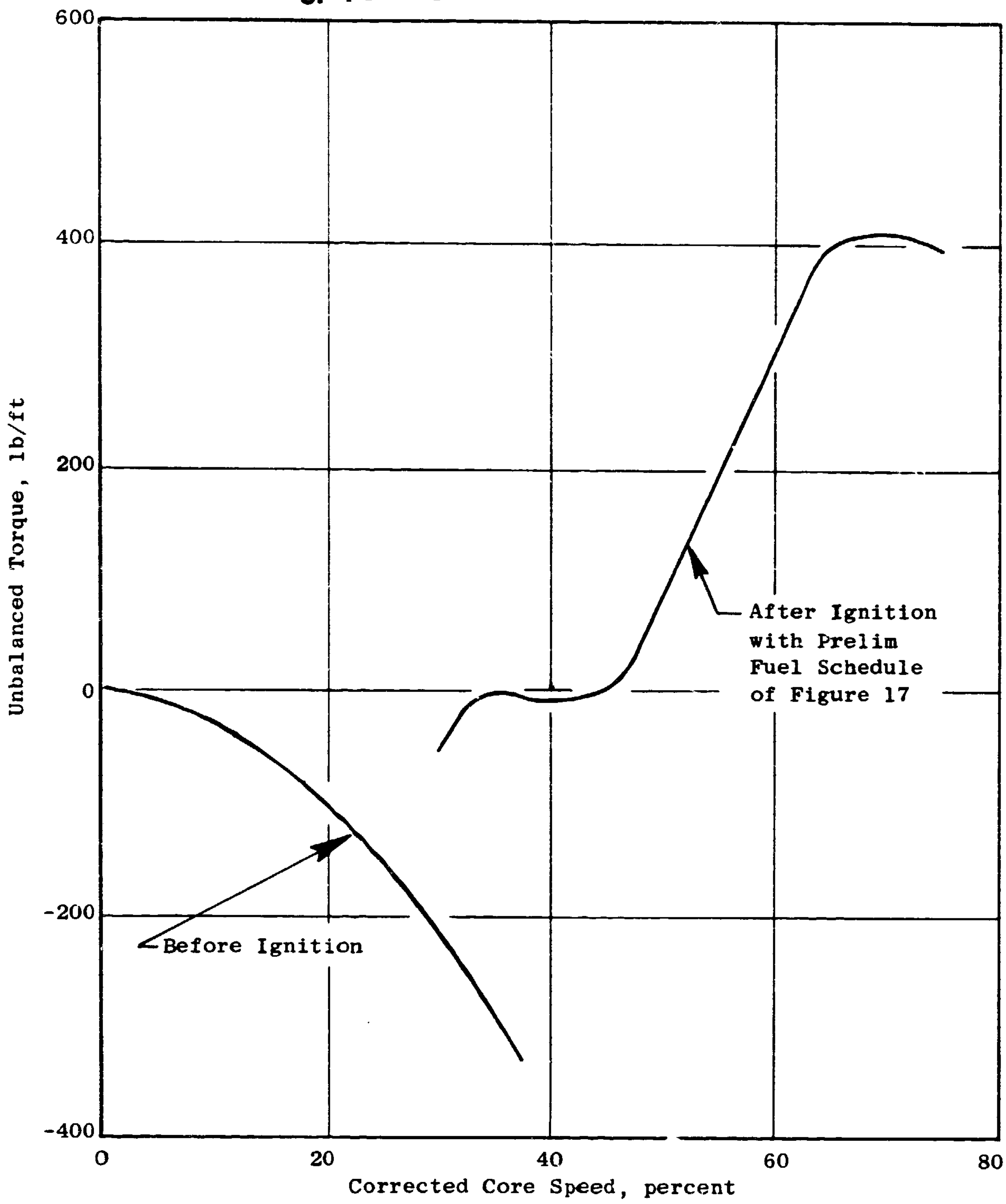

Figure 18. Torque Data from Subidle Model.

6.0 CONTROL OF COMPRESSOR STATOR VANES

6.1 COMPRESSOR STATOR ACTUATION AND CONTROL

On the core and ICLS engines the compressor IGV's and the first six stator stages are variable and ganged by a system of levers and annular rings around the compressor so that the stages move simultaneously with a stage-to-stage relationship established by linkage characteristics. As shown in Figure 19, the linkage is operated by a pair of fuel-driven ram actuators that are normally controlled by the digital control through an electrohydraulic servovalve. Position feedback to the control is provided by a position transducer connected to the actuation linkage. In the event of a digital control system failure, control of the stator actuators transfers to the hydromechanical control which provides a basic schedule similar to that in the digital control. This is described further in Section 10.

6.2 COMPRESSOR STATOR CONTROL STRATEGY

The conventional practice of scheduling compressor stator angles as a function of rpm and inlet temperature is used for the E^3, but the added computational capability offered by the digital control is utilized to supplement the basic schedule and to further exploit the potential of variable stators to improve engine operation and performance.

Figure 20 is a block diagram of the stator control strategy. The basic schedule is shown in the next-to-top block on the left with the modifiers applied to it through downstream summations. The modifiers are described below.

Approach Reset - This feature in effect provides an alternate schedule that closes the vanes much further than normal in the approach thrust range. This results in higher core rpm during approach, thus making it possible to regain high thrust more quickly in the event of an aborted landing. This concept, tried briefly during the NASA/GE QCSEE program, is included in the E^3 program so that it can be explored further.

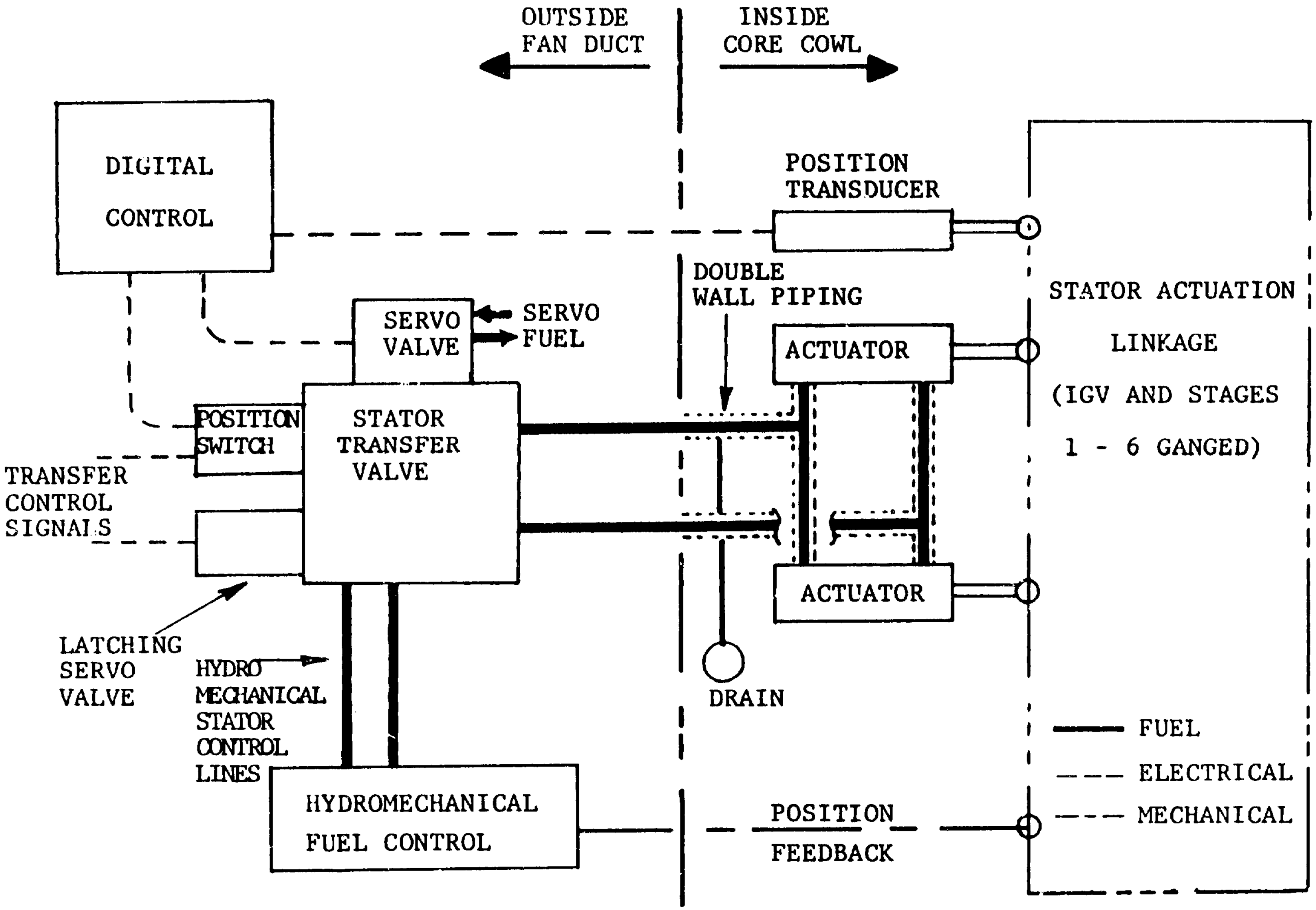

Figure 19. Compressor Stator Actuation and Control.

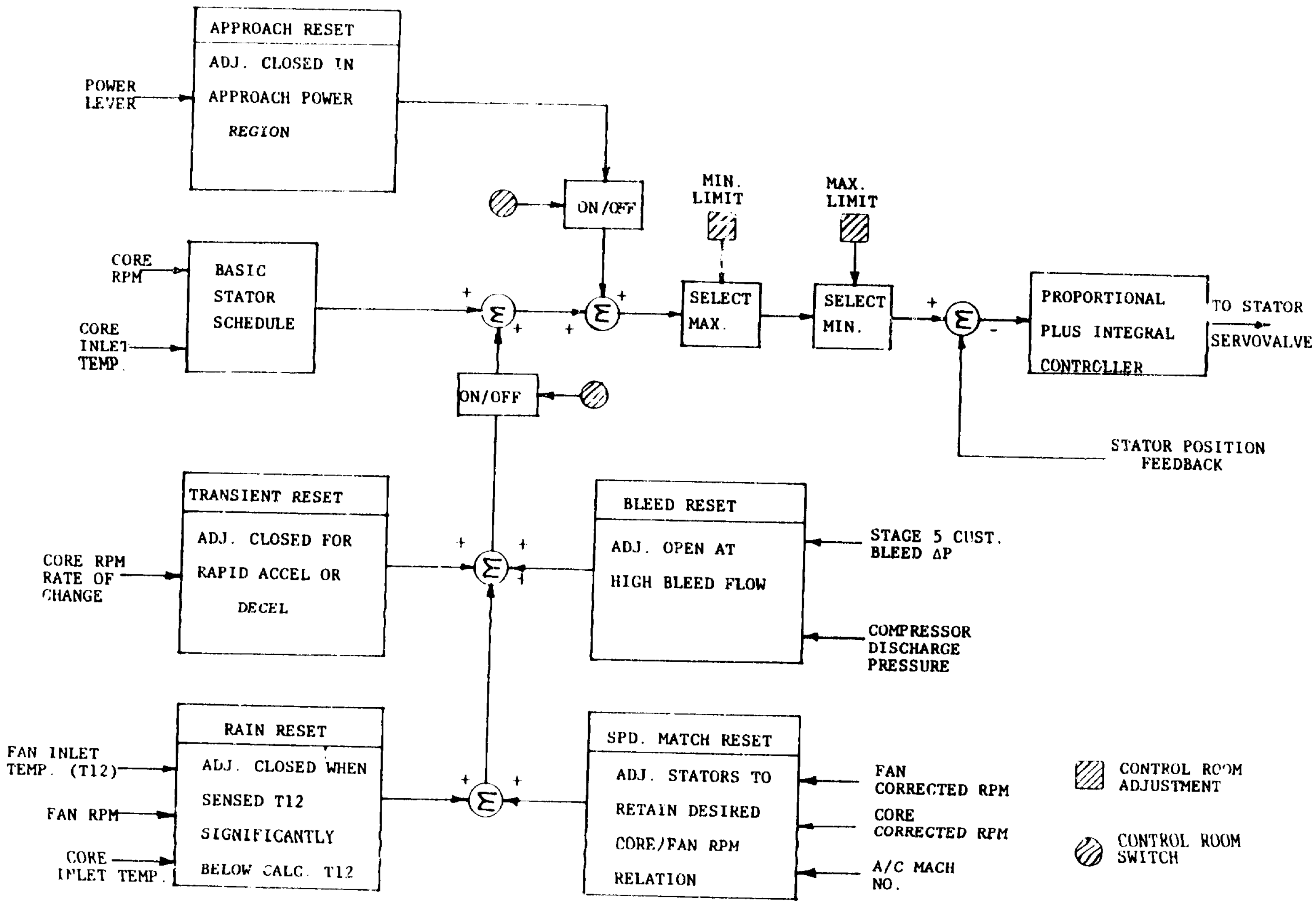

Figure 20. Compressor Stator Control Strategy.

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Rain Reset - Experience with CF6 engines has shown that heavy rain causes a reduction in compressor inlet temperature (T25); rapid termination of rain, combined with T25 sensing lag, can cause compressor stalls. This reset causes a small stator vane closure when sensed T25 is less than calculated T25 (as it will be in heavy rain), thereby increasing stall margin.

Speed Match Reset - Experience has shown that engine deterioration often results in a reduction core rpm relative to fan rpm and a corresponding reduction in core efficiency at cruise thrust settings. This function detects a deviation from the normal core rpm/fan rpm relationship and adjusts the stator vanes to restore the original relationship.

Bleed Reset - It has been proposed that a stator vane reset might be used to adjust the compressor operating point and to improve efficiency when customer bleed air is being extracted. This function is included to allow investigation of this concept.

Transient Reset - The basic stator schedule is designed to provide optimum steady-state compressor performance. But it is not necessarily the best schedule for rotor speed transients. For this reason, a transient schedule reset is proposed to provide improved transient characteristics. Because stator effects on the E^3 compressor are not yet accurately known, analytical definition of the reset is not presently feasible. Based on past experience, it is expected that a stator reset in the closed direction will provide additional transient surge margin and better transient characteristics. A reset proportional to the rate of change of speed is incorporated for empirical evaluation.

Switches are provided as shown on the block diagram (Figure 20) to allow the above modifiers to be disabled during the test program so that they cannot interfere with normal stator scheduling. Also, adjustments are included (not shown on diagram) to eliminate the effects of individual modifiers.

7.0 CONTROL OF STARTING BLEED

7.1 START BLEED ACTUATION AND CONTROL

The E^3 incorporates provisions for bleeding air from the compressor 7th stage in order to compensate for flow mismatch between the front and rear stages at low speeds during a start. This bleed flow is controlled by a set of four butterfly valves that are connected in parallel as shown schematically on Figure 21. The valves are incorporated into four radial air pipes that connect the Stage 7 bleed manifold with ports on the inner wall of the fan duct. The actuation ring that connects the valves is driven by a single fuel-powered servoactuator; the control signal for the servoactuator is provided from the digital control. An electrical position transducer is incorporated within the servoactuator to provide feedback to the control.

7.2 STARTING BLEED CONTROL STRATEGY

The automatic control strategy for the starting bleed calls for positioning the valves, thereby controlling bleed flow as a function of core-corrected rpm. This is shown in the block diagram, Figure 22; the initial schedule is shown on Figure 23. Scheduling flexibility for the test program is provided by digital control adjustments of the open flat and the location of all break points on this schedule.

In addition, a manual control mode for the start bleed valves is provided to allow experimentation during the engine test program. In this mode, the bleed valves are positioned in response to a potentiometer on the digital control operator panel in the control room.

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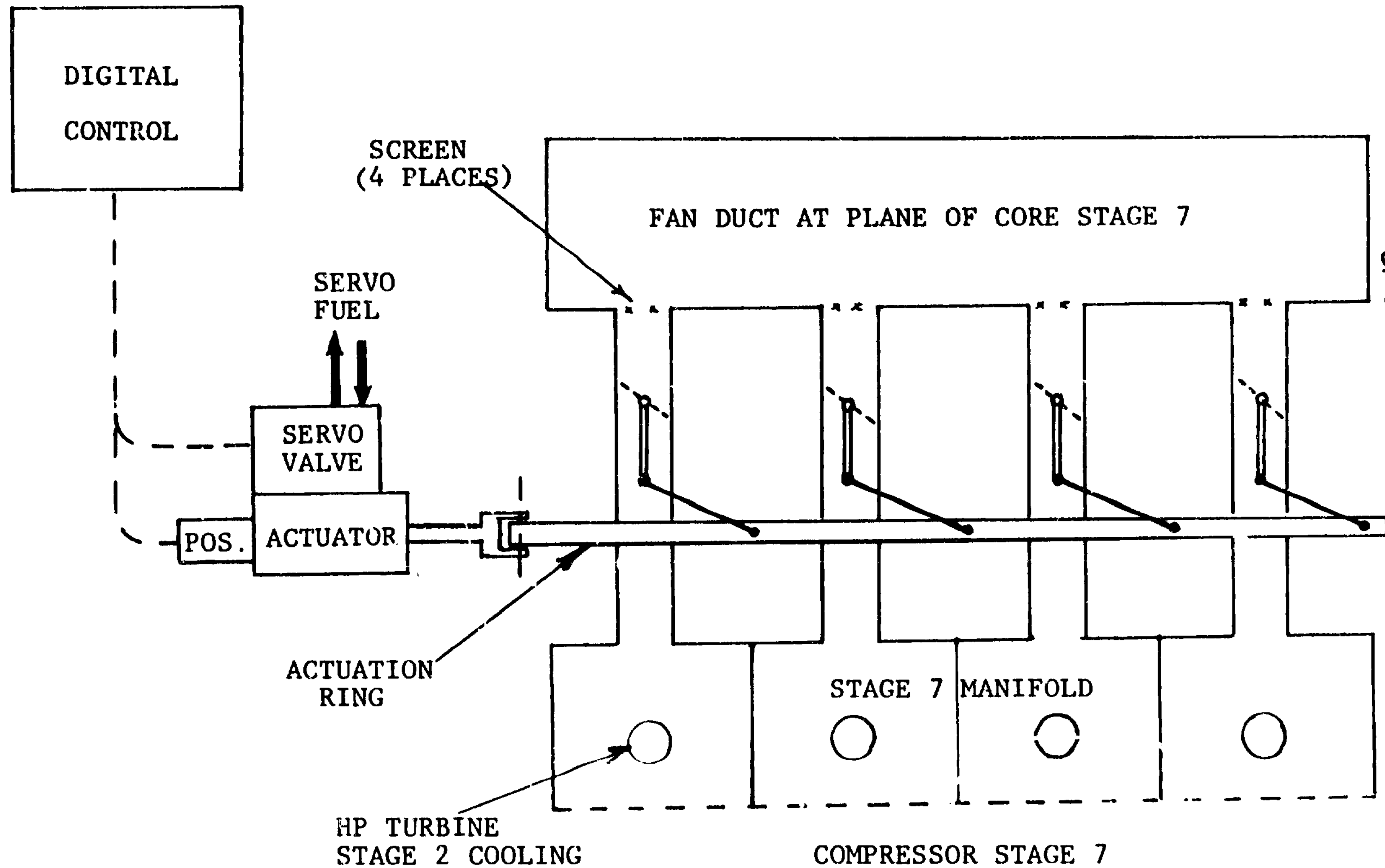
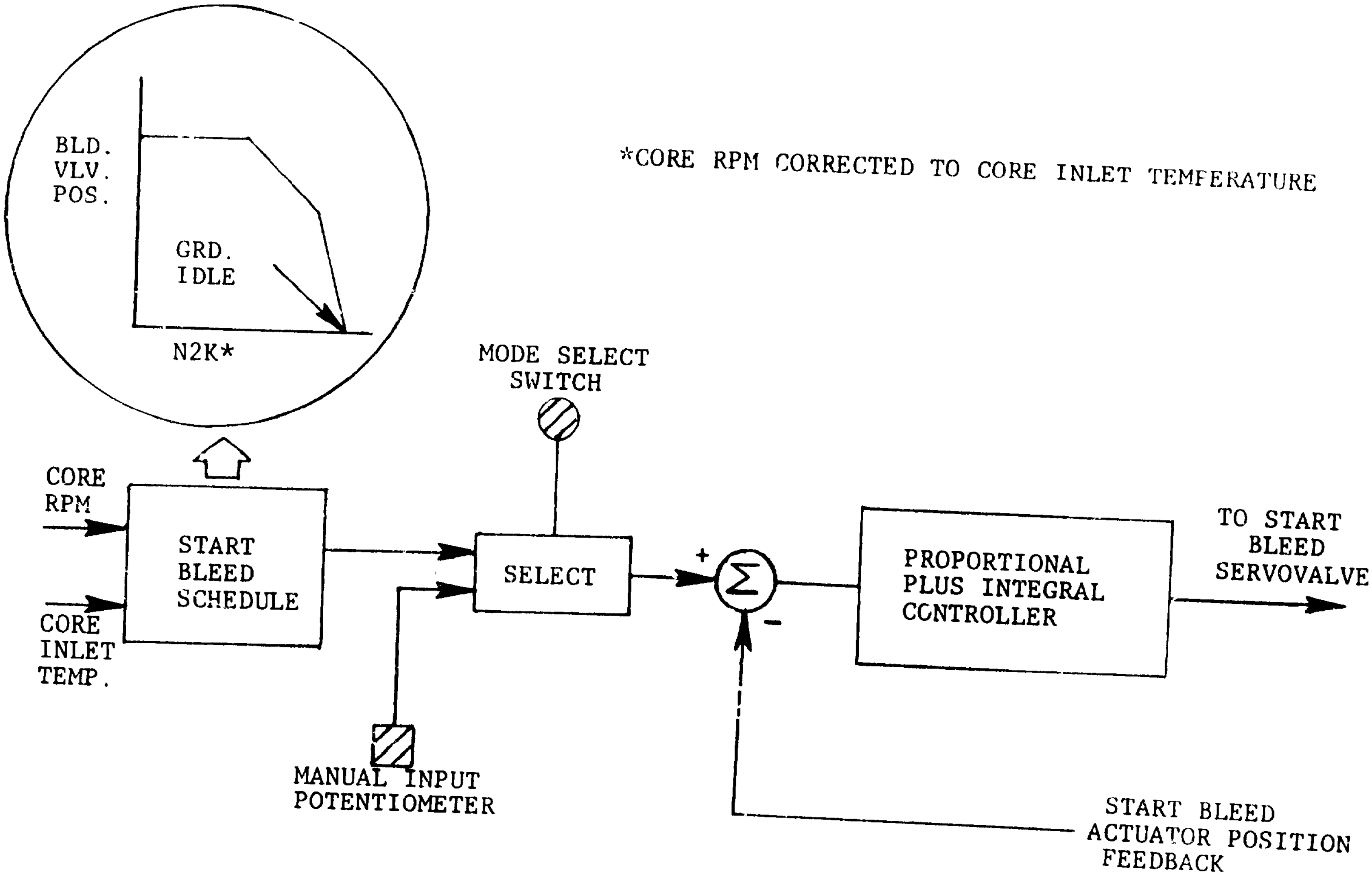


Figure 21. Starting Bleed Control system.



*CORE RPM CORRECTED TO CORE INLET TEMPERATURE

Figure 22. Starting Bleed Control Strategy.

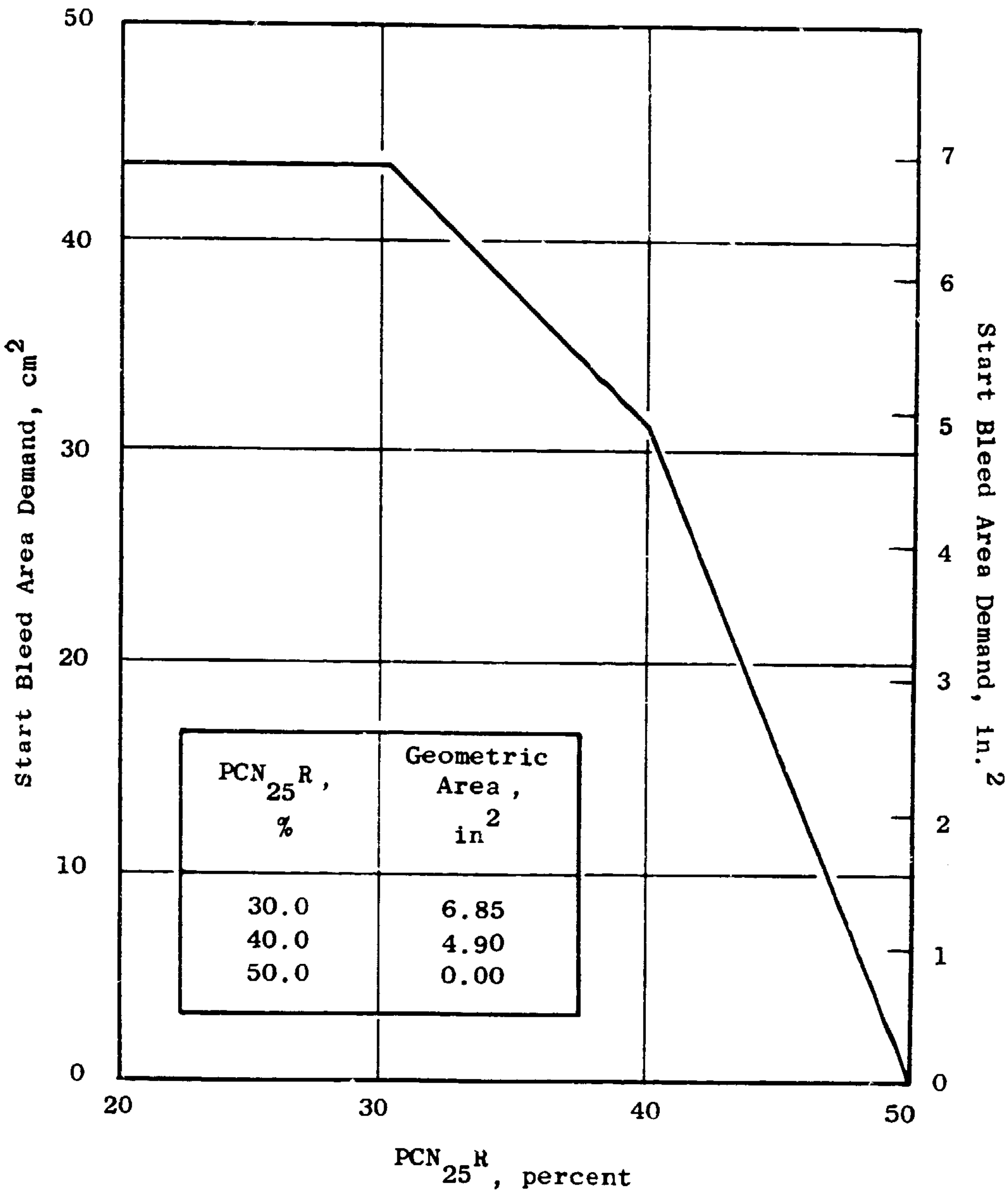


Figure 23. Starting Bleed Schedule.

8.0 CONTROL OF START RANGE TURBINE COOLING

8.1 START RANGE TURBINE COOLING MECHANIZATION

One of the effects of the starting bleed just described is to lower pressure levels throughout the compressor when the bleed is open. This has a corresponding effect on the pressure level and on the flow of air extracted from the compressor and piped externally to the turbine region for cooling and internal pressure control. Figure 24 shows these parasitic flow systems schematically. A small amount of Stage 5 air, also used for compressor clearance control, is piped into the LPT purge manifold and used for internal pressure control in the LPT rotor. Also, a small amount of Stage 7 air is piped to the Stage 2 HPT stator for cooling.

In order to maintain adequate pressure and flow in the parasitic air systems during a start with the start bleed valves open, provisions are made to temporarily connect these systems to a higher pressure source. A pair of air-actuated on-off valves and a system of check valves allow compressor discharge pressure to be applied to the parasitic systems when the start bleed valves are open. Actuation air for the two start range turbine cooling valves is controlled by a digital control-operated solenoid valve.

8.2 START RANGE TURBINE COOLING CONTROL

Two control modes are provided for the start range turbine cooling, one automatic and the other manual. In the automatic mode the source for the parasitic air systems is selected as a function of core-corrected rpm. Below ground-idle power the systems are connected to compressor discharge pressure; at ground idle and above, they are connected to their normal sources. A slight delay in closing the start range turbine cooling valves is provided upon reaching ground idle to prevent any undesirable compressor discharge pressure disturbances before steady-state operation is achieved.

In manual mode, start range turbine cooling valves are controlled solely by a switch on the digital control operator panel.

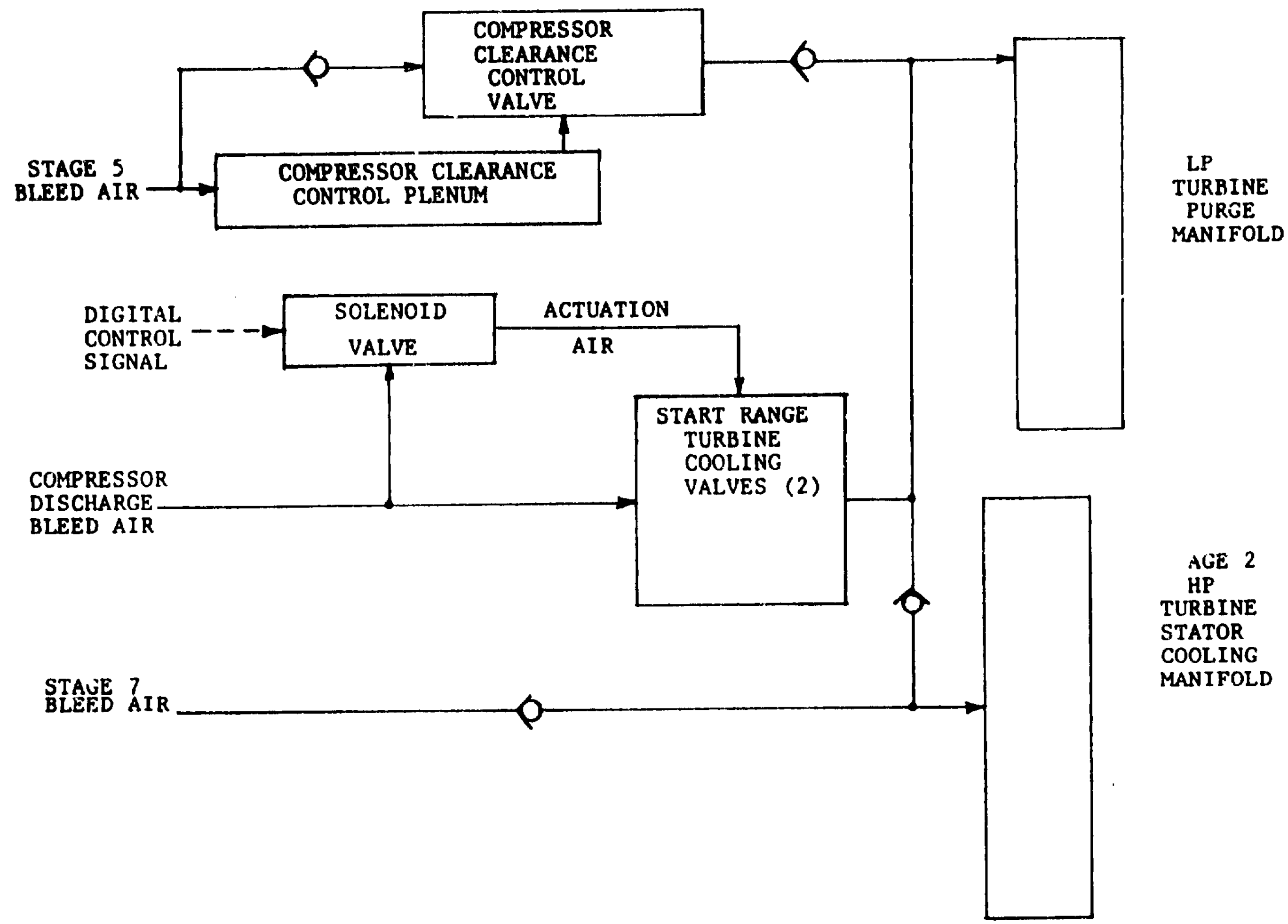


Figure 24. Start Range Turbine Cooling System.

9.0 ACTIVE CLEARANCE CONTROL

9.1 ACTIVE CLEARANCE CONTROL MECHANIZATION

There are three separate active clearance control systems on the E^3: one for the aft stages of the compressor, one for the HP turbine, and one for the LP turbine. They are shown schematically on Figure 25.

Clearance control in compressor Stages 6 through 10 is achieved by passing a variable flow of Stage 5 bleed air over the compressor casing in this region to provide a thermal adjustment of casing dimensions. The Stage 5 air extracted for LPT purge is ported so that it can flow through the compressor clearance control chamber and through an external bypass pipe. Air from these two flowpaths is ported to a rotary three-way valve which is designed to provide virtually constant total flow but a flow split between the two flowpaths that varies with valve rotor position. The valve is positioned by a fuel-operated servoactuator controlled by the digital control. An electrical transducer within the actuator provides position feedback to the control.

Turbine clearance control is achieved by impinging variable amounts of air, independently, onto the HP and LP turbine casings to provide thermal control of casing dimensions. Both systems utilize fan discharge air picked up by scoops in the fan duct pylon wall and passed through variable area butterfly valves. These valves are independently positioned by fuel-operated servoactuators similar to the one used for compressor clearance control. The HPT clearance control system also includes a provision for introducing compressor discharge air onto the casing. Studies, using the clearance model described below, revealed the desirability of using this air for a brief period immediately after engine start in order to establish proper clearances quickly and, thereby, eliminate the possibility of a rub if the engine is accelerated before the casing can heat up naturally. The studies showed a similar feature which was not needed for the LP turbine.

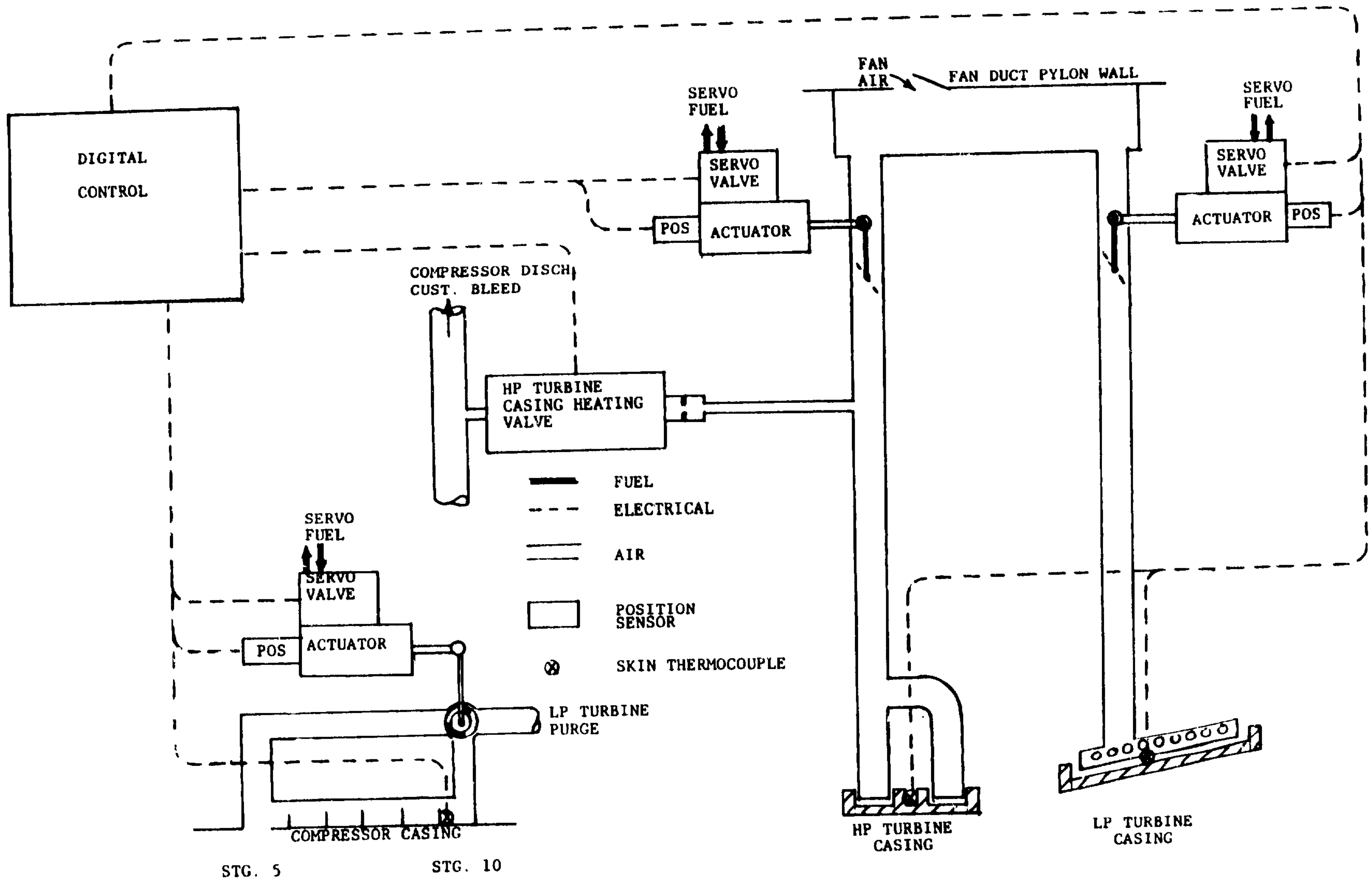


Figure 25. Clearance Control System.

9.2 CLEARANCE CONTROL STUDIES AND CONTROL STRATEGY DEFINITION

The process of defining a control strategy for the clearance control systems began with the establishment of a set of general objectives as listed below.

- Provide minimum practical clearance at cruise power settings.
- Provide extra clearance for takeoff/climb maneuver deflections.
- Prevent hot rotor reburst rubs.
- Fail-safe (i.e., to maximum clearance).
- Provide manual remote control of clearance air valves for core/ICLS experimental flexibility.

In proceeding with the task of defining a control strategy for the clearance control systems, consideration was given to the use of direct clearance sensing to provide feedback information to the digital control and thus allow direct control of clearances. Clearance sensing on an operating engine has been demonstrated on an experimental basis, but the methods are not far enough along in development to make them feasible for use on initial E^3's. Thus, it was necessary to develop a control strategy that does not depend on clearance sensing.

To assist in the definition of clearance control strategy, mathematical models of the engine and control elements involved in active clearance control were utilized. A generalized model was established which uses rotor speed, altitude, and Mach number as its inputs and which combines dynamic representations of internal flows, heat transfer, thermal growth, and mechanical growth to arrive at calculated clearance values. A diagram of the generalized model adapted for the compressor is shown in Figure 26.

The engine model is a compilation of corrected parameters representing the pertinent cycle interfaces (T25, T3, P25, P3, P8 for the compressor) as functions of corrected core speed (XNHR). Included is a derivation of the pressure and temperature distribution in the engine flowpath at each stage. The cycle variable tabulations are for specific altitude and Mach numbers and are generated as a cycle deck operating line. A procedure was established to

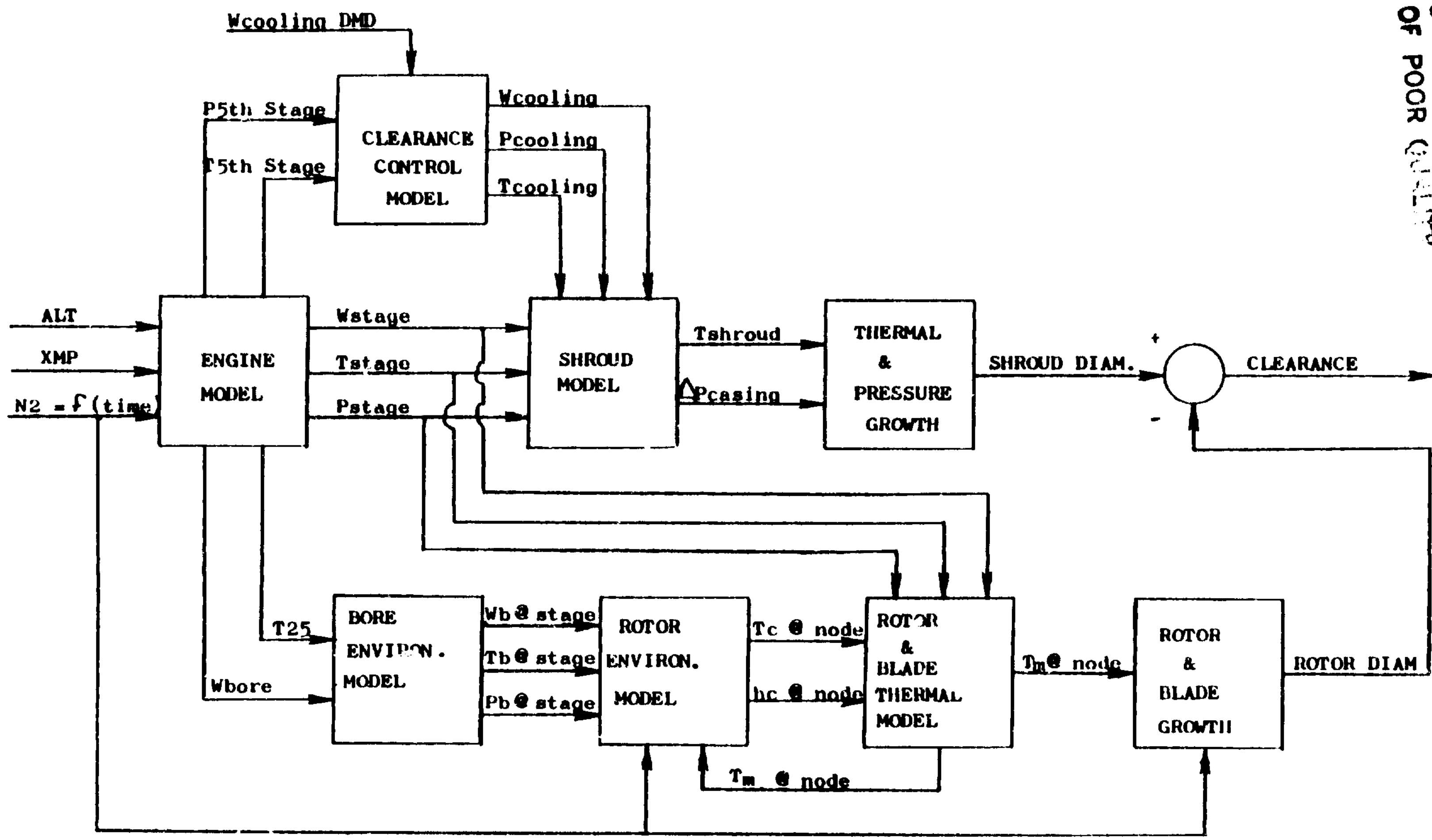


Figure 26. Clearance Model.

convert cycle deck output to files of tabulation that are readily incorporated into the engine model.

The bore environmental model establishes the transient temperature distribution in the bore flowpath in a stage-by-stage thermal analysis of the disks. Each disk is simulated as a nodal pair (bore rim) for this purpose. The routine includes an iteration on bore flow level, which depends on the bore path exit temperature.

The rotor environmental model incorporates a representation of the immediate neighborhood, fore and aft of the detail stage disk. It invokes the bore environmental model to establish bore path conditions at the detail stage from which the pressure and temperature distributions in the interdisk cavities are determined. The convectance and temperature at each disk node site is established for the determination of nodal resistances in the rotor/blade thermal model.

The rotor/blade thermal model uses the resistance values from the rotor environmental model to calculate the node-by-node temperature distribution in the rotor disk. The resistance/capacitance values at each disk node are constructed from boundary resistances (convectances and conductances) and internal conductances. The blade is thermally coupled to the engine flowpath and through the shank to the disk rim node.

The rotor/blade growth model is used to calculate the radial growth of the rotating parts. The radial growth of the disk is calculated as a function of radial load at the rim, temperature distribution, and angular velocity. Growth of the blade is determined by the conventional relationship:

$$\Delta = \ell\alpha\,(T - T_o)$$

where T is the element temperature, To the temperature at assembly, ℓ the blade length, and α the coefficient of thermal expansion.

The clearance control model schedules and determines the impingement cooling air supply. The shroud model includes interaction with the engine flowpath and provision for impingement cooling of any designated casing.

Transient effects for the impingement air were also modeled. Thermal growth of the shroud is determined in the same manner as blade growth. Then, clearance is simply the shroud diameter minus the rotor/blade diameter.

The generalized clearance model was validated through the use of CFM56 compressor clearance experimental data gathered during engine running. The CFM56 characteristics were introduced into the model and the model was run at the conditions existing when the experimental data was taken. Initial runs revealed that some of the model representations needed refinement. After the refinements were made the model matched the experimental data for both transient and steady-state conditions. It was then considered suitable for transformation to E^3 compressor and turbine configurations and for use in exploring E^3 clearance control system characteristics.

Typical data from the E^3 clearance model is shown in Figure 27. This happens to be for the HPT, but it is typical of all three systems. It shows that the system is capable of modulating the steady-state clearance at takeoff conditions from 0.279 to 1.346 mm (0.011 to 0.053 in.) with the fan air bleed flow within the range established by engine cycle considerations (0.3% of core airflow, maximum). This figure also shows that clearance during and immediately after a rapid rotor acceleration with a given amount of cooling is much less than the steady-state clearance with that same amount of cooling. The maximum cooling condition shown actually results in an interference at the end of the acceleration. In order to eliminate the potential for such interference, the model data suggests that a limit must be imposed on cooling as a function of rpm. Figure 28 shows just such a limit.

As might be expected, the model also revealed that an orderly relationship exists between steady-state clearance, casing temperature, and rotor rpm (shown by the solid lines in Figure 29). The characteristics shown here suggest that a schedule of casing temperature as a function of rotor rpm could serve as an indirect method of controlling clearance. A trajectory for such a schedule is shown on Figure 29. The trajectory was established on the basis of the following criteria:

- Set the desired minimum running clearance of 0.406 cm (0.016 in.) at maximum cruise conditions.

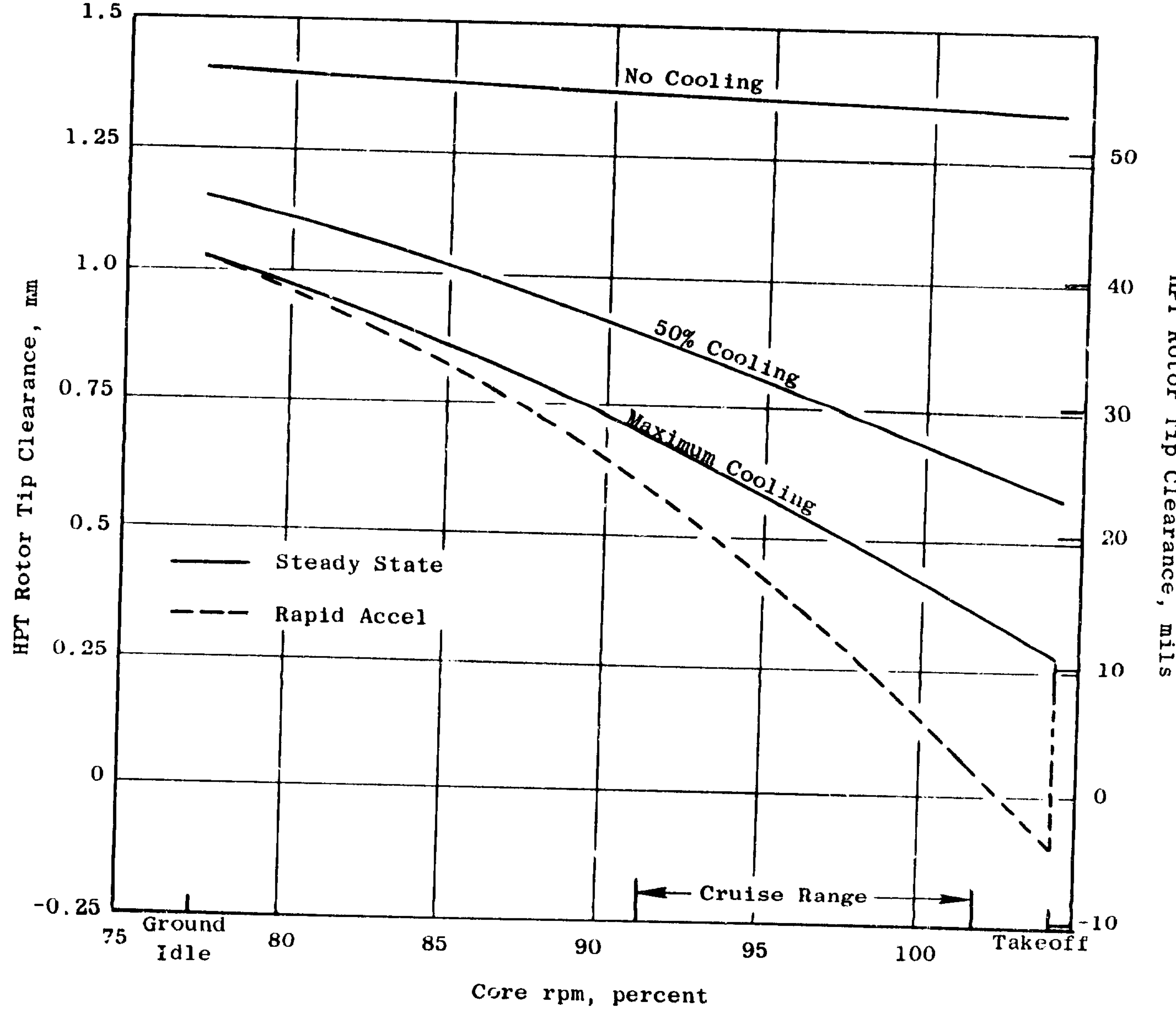


Figure 27. Preliminary HP Turbine Clearance Control Characteristics.

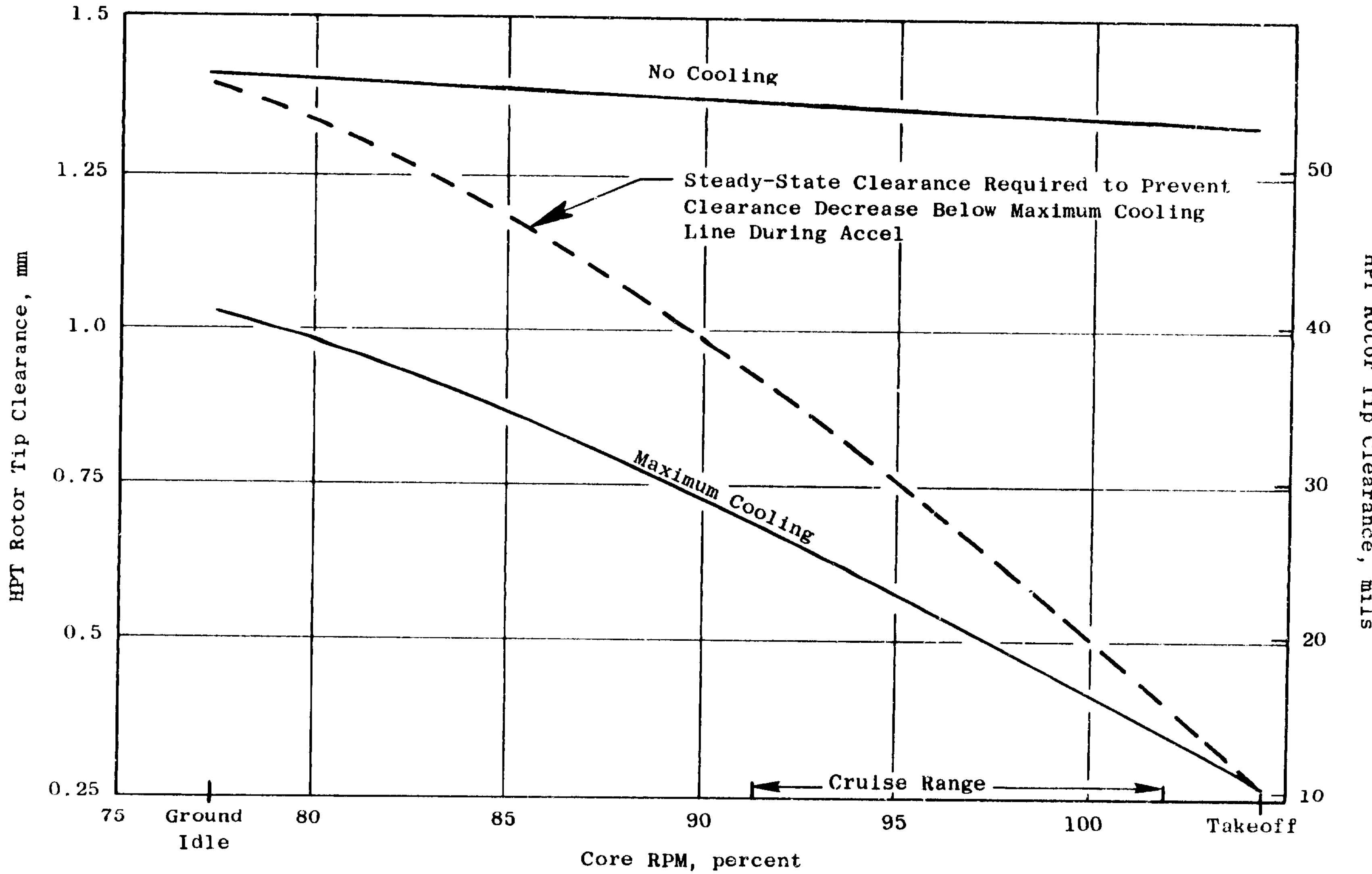


Figure 28. Preliminary HP Turbine Accel Clearance Margin Curve.

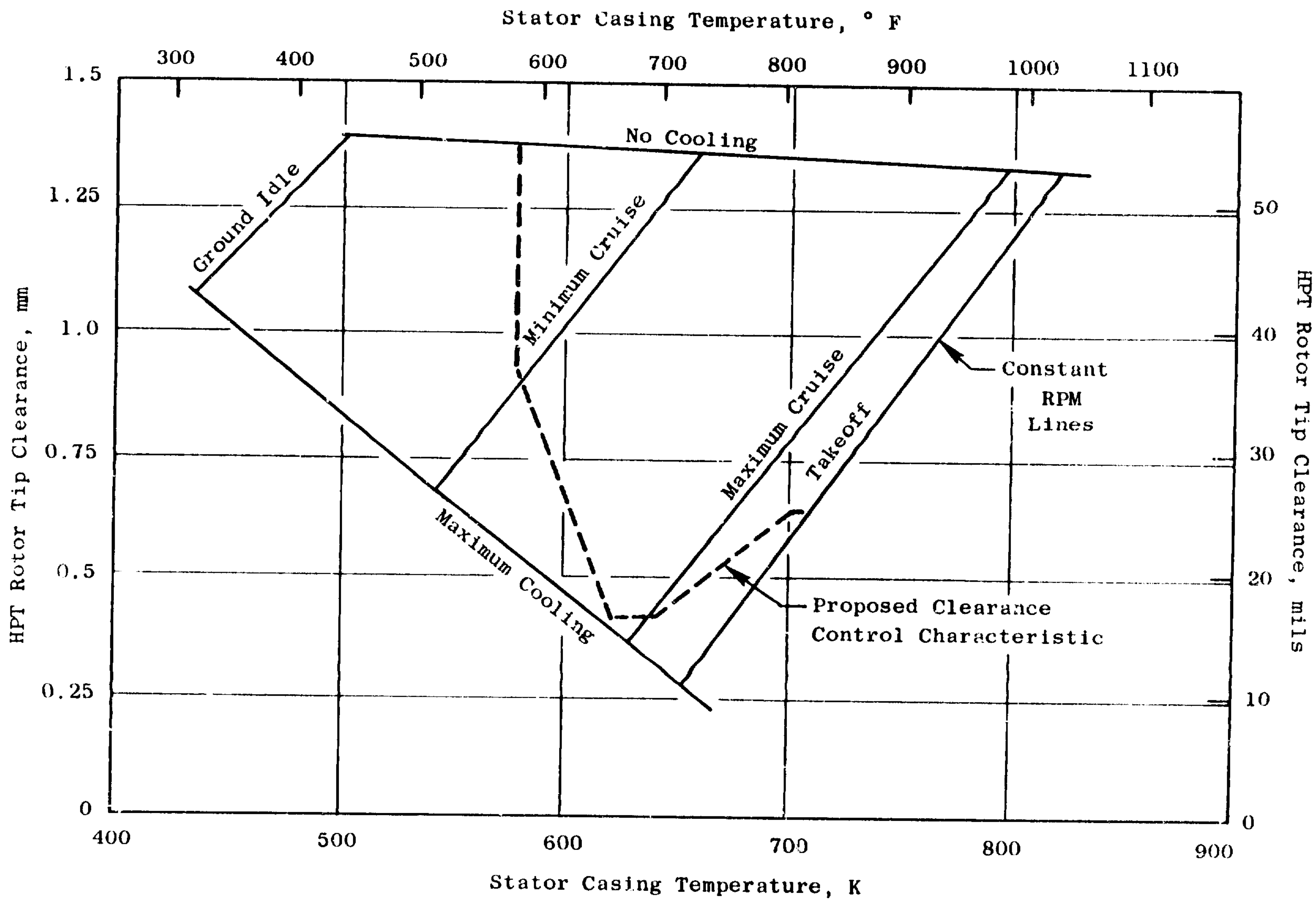


Figure 29. Preliminary HP Turbine Clearance Control Characteristic.

- Provide additional clearance up to 0.635 mm (0.025 in.) at takeoff and climb conditions to accommodate maneuver deflections.

- Set additional clearance at lower cruise power settings to prevent inadequate clearance transiently after an acceleration.

- Provide maximum clearance at power settings below cruise to provide ample margin for accelerations. (Very little of the total engine fuel consumption during normal flights occurs in this power setting region; thus, the extra clearance margin has negligible effect on fuel use.)

The initial schedule derived in this manner is shown in Figure 30. Note that the schedules are defined in terms of parameters corrected to core engine inlet temperature. Similar schedules were derived in the same manner for compressor and LPT clearance control.

In order to assess the transient effects of scheduling casing temperature (and thus steady-state clearance) in the manner just described, the schedules were incorporated into the clearance model and transients were run. Figure 31 shows typical data from the HPT clearance model during an acceleration. This data reveals another desirable characteristic of the casing temperature scheduling concept. For nearly three minutes after an acceleration from idle to takeoff power, the casing temperature is below schedule and the clearance control valve is closed. The thermal characteristics without casing cooling are such that clearance remains in the 0.635 to 0.762 cm (0.025 to 0.030 in.) range, thereby providing the additional margin desired for the engine deflections that occur during takeoff and initial climb.

Accel transient runs on the compressor clearance model also revealed an interesting characteristic. As shown in Figure 32, the temperature of the Stage 5 clearance control air is higher than casing temperature for about a minute after an acceleration from idle to takeoff power. By rotating the clearance control valve to the maximum casing flow position during this period, casing growth can be accelerated to help provide the extra clearance margin desired for takeoff and initial climb. A model run showing the effect of this feature is shown in Figure 33.

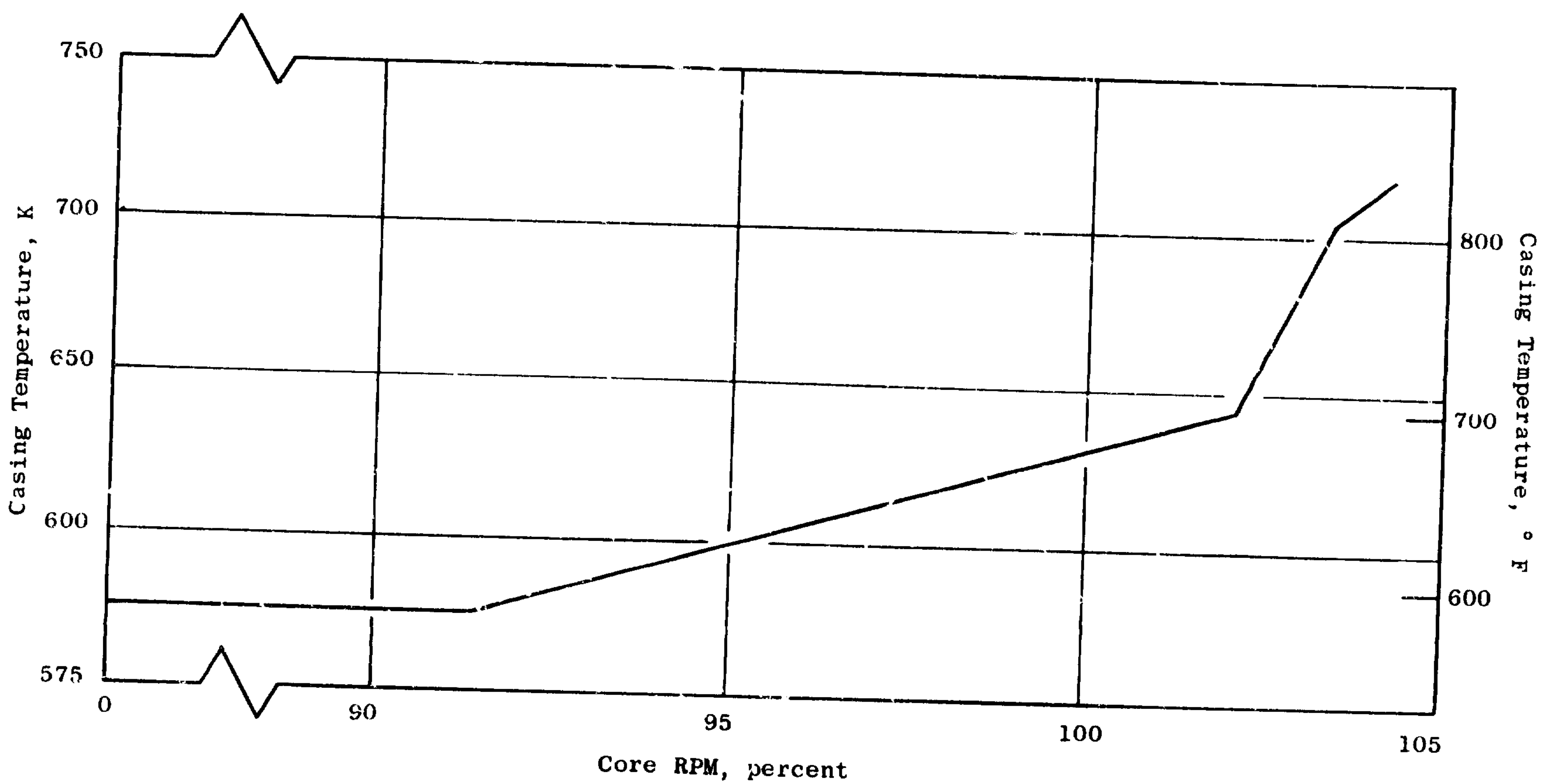


Figure 30. Preliminary HP Turbine Clearance Control Schedule.

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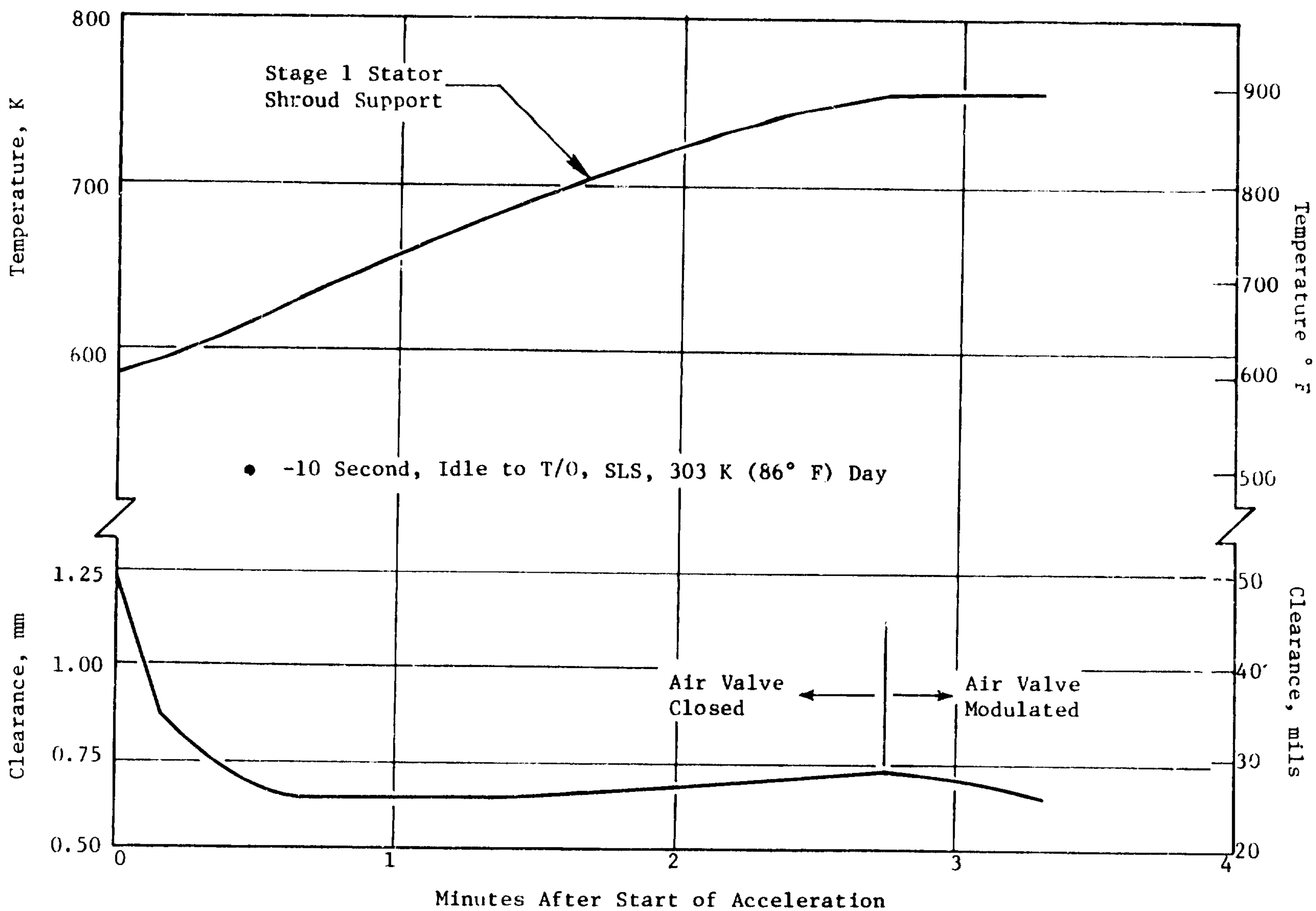

Figure 31. Transient HP Turbine Clearance and Temperature.

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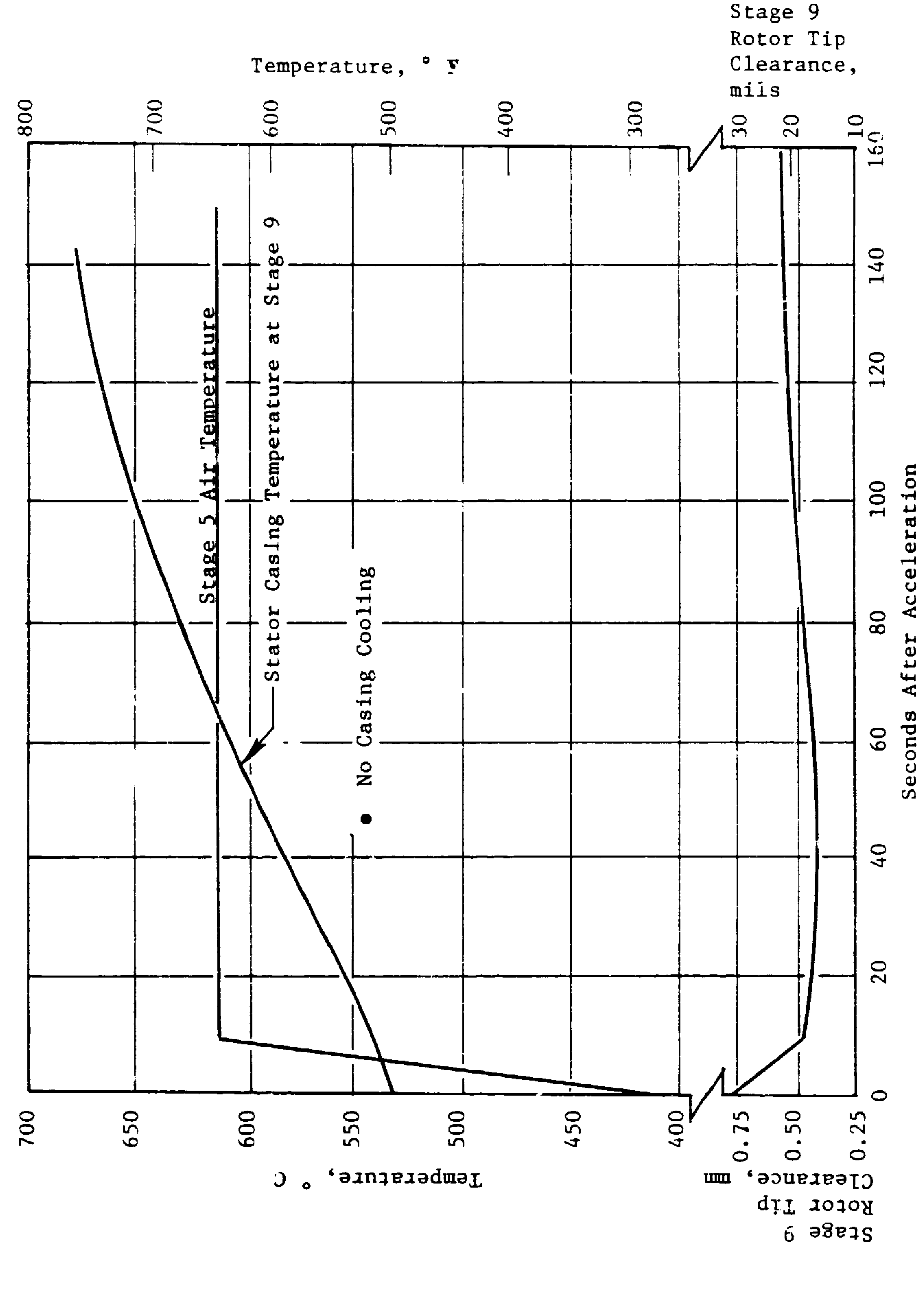

Figure 32. Compressor Clearance Characteristics.

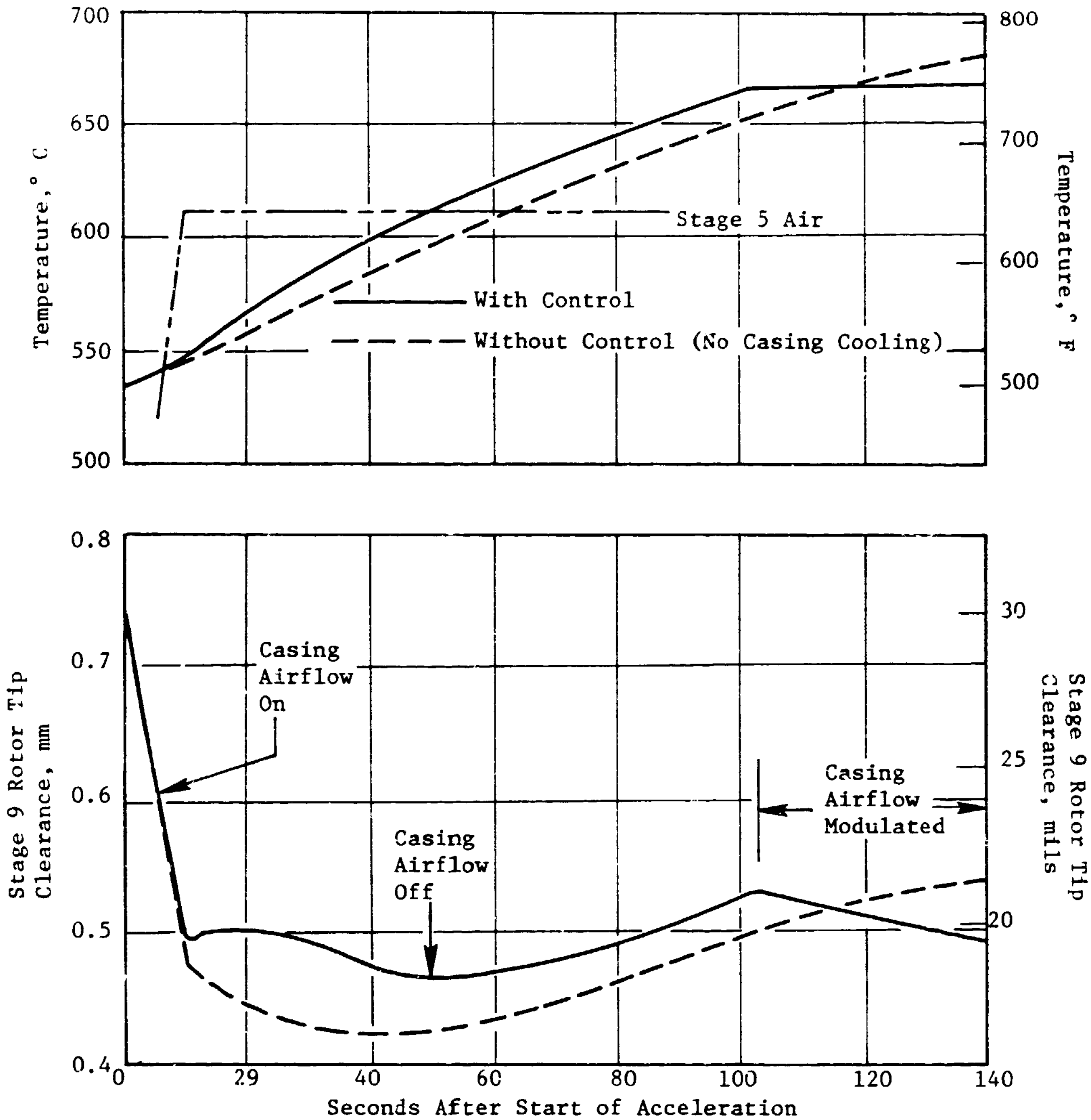

Figure 33. Transient Compressor Clearance With and Without Control.

With the casing temperature scheduling concept successfully demonstrated on the clearance model, detailed clearance control strategy definition proceeded. Figure 34 is a block diagram of the strategy for the HPT clearance control systems. The basic casing temperature scheduling function is shown in the upper left part of the diagram. The decel override shown below this was added to prevent rubs in the event of hot rotor reburst (that is, a deceleration followed by an acceleration before the rotor, which cools slower than the casing, has reached steady-state temperature). A rapid deceleration causes the clearance control valve to close and remain closed until the casing temperature reaches the normal steady-state level. If the engine is reaccelerated before steady-state temperatures are established, the decel override is deactivated and the casing temperature schedule functions normally.

A manual control mode is also provided. When the manual mode is selected, the air valve is positioned as a function of a potentiometer on the digital control operator panel in the control room so that clearance control system characteristics can be experimentally evaluated. A decel override is included in the manual mode to preclude a hot rotor reburst with the air valve inadvertently left open after a decel. This override, once activated, remains in effect until manually reset.

In addition, the block diagram of Figure 34 shows the casing heating features that provides quick warmup after an engine start so that an immediate acceleration to high speed can be made without encountering a rub. In the automatic control mode, this on-off function is triggered as a function of casing temperature with the valve open below steady-state idle temperature and closed above. A manual mode is also provided. The casing heating feature will not be included on the test engines but would be part of a production engine design.

The control strategy for the LP turbine is functionally the same as for the HP turbine, except that no casing heating feature is included. Clearance model runs showed this rapid poststart warmup is not necessary for the LP turbine.

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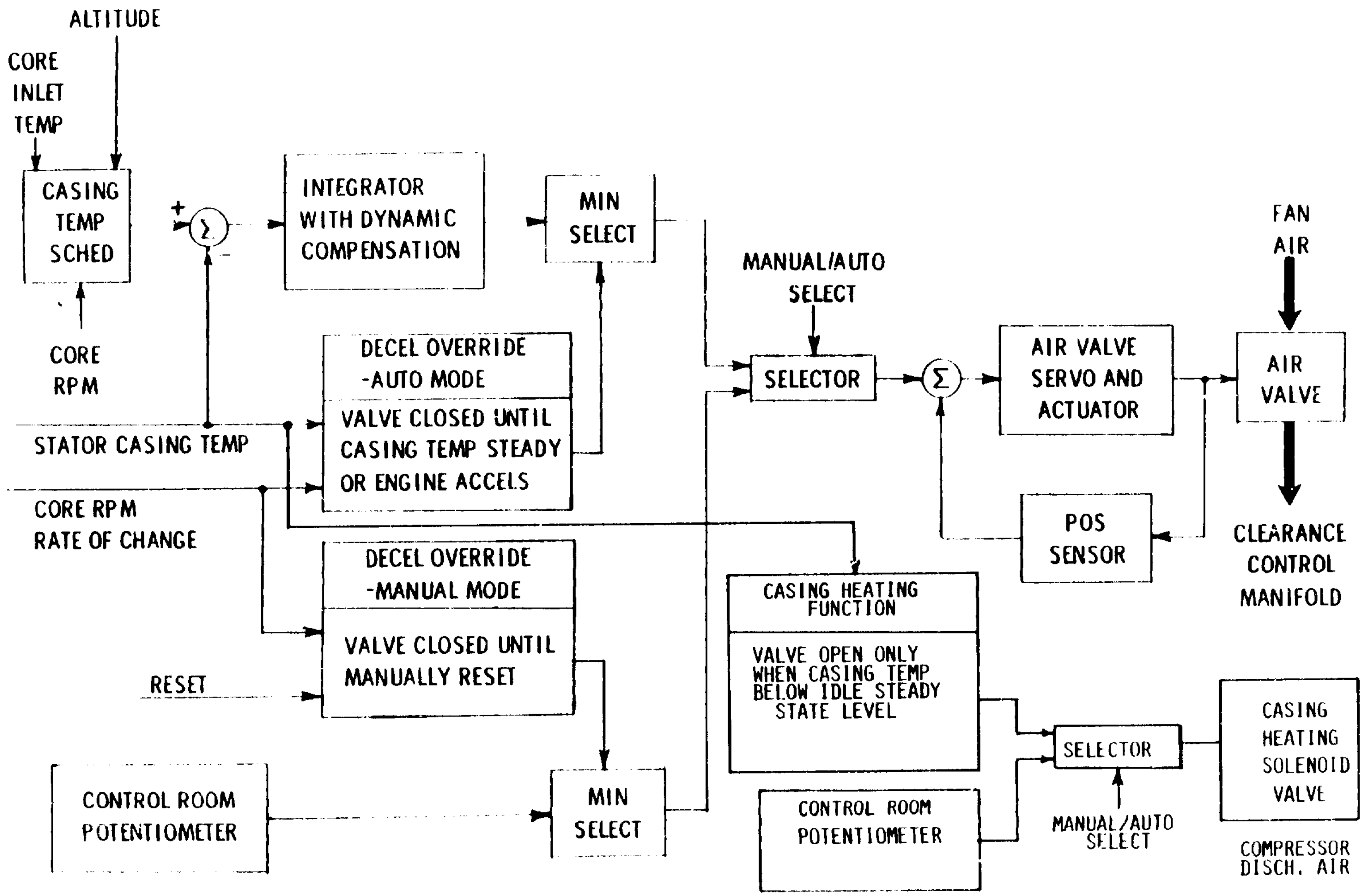


Figure 34. Turbine Clearance Control.

Figure 35 shows the control strategy for the compressor clearance control. It includes a basic casing temperature regulator, a decel override, and a manual mode that all function the same as those in the turbine clearance control systems. In addition, it includes an air temperature override which positions the valve to cause clearance control air to flow over the casing when the air temperature exceeds the casing temperature. This is the extra acceleration margin feature described earlier. To eliminate the need for a clearance control air temperature sensor, this temperature is calculated from compressor discharge pressure and compressor inlet temperature, both of which are already sensed by the control system for other reasons.

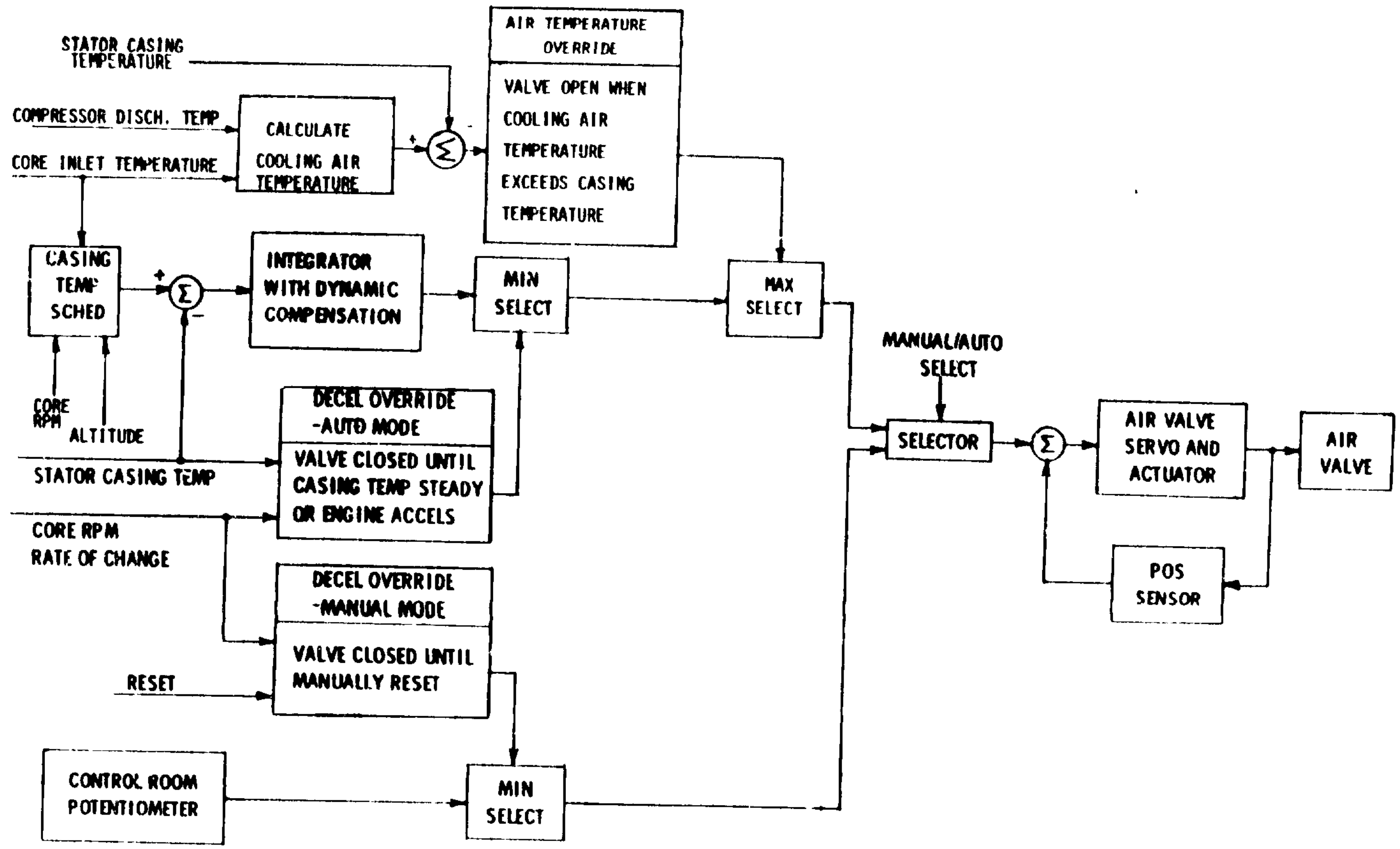


Figure 35. Compressor Clearance Control.

10.0 FAILURE PROTECTION

Protection against failures that can cause control or engine operational problems is an important aspect of any control system design. For the E^3 system this is particularly important because the digital control and associated elements are in a relatively early stage of development. Control redundancy is one conventional means of providing such protection; hence, dual redundant digital controls are proposed for the production engine system. Because the definition and implementation of redundancy was considered beyond the scope of the present E^3 program, less costly failure protection features were incorporated for the core and ICLS engines. These are described in the paragraphs below.

10.1 HYDROMECHANICAL BACKUP CONTROL

The E^3 test engine control system includes an F101 hydromechanical main engine control which is used primarily for its fuel metering section, controlling fuel flow in response to a signal from the digital control. The control also includes a hydromechanical computing section. This section is employed to provide backup control of fuel flow and core stator actuator position. Figure 36 is a general schematic of the backup system. Figures 37 and 38 show additional functional details.

In the primary mode, the latching solenoid valve positions the transfer valves so that the fuel metering valve and the core stator actuators are controlled by the digital control through the electrohydraulic fuel and stator servovalves. When the latching solenoid is energized to the backup position, the transfer valves move to their backup position. Here the fuel metering valve and core stator actuators are both controlled hydromechanically by the fuel control. In this condition a position switch on the stator transfer valve signals the digital control to deenergize all outputs so that built-in offsets in the output devices cause all other controlled variables to go to safe positions. The valves controlling fuel flow split go to the full burning condition, the start bleed and start range turbine cooling valves close, and the clearance control valves go to the maximum clearance position. The latch

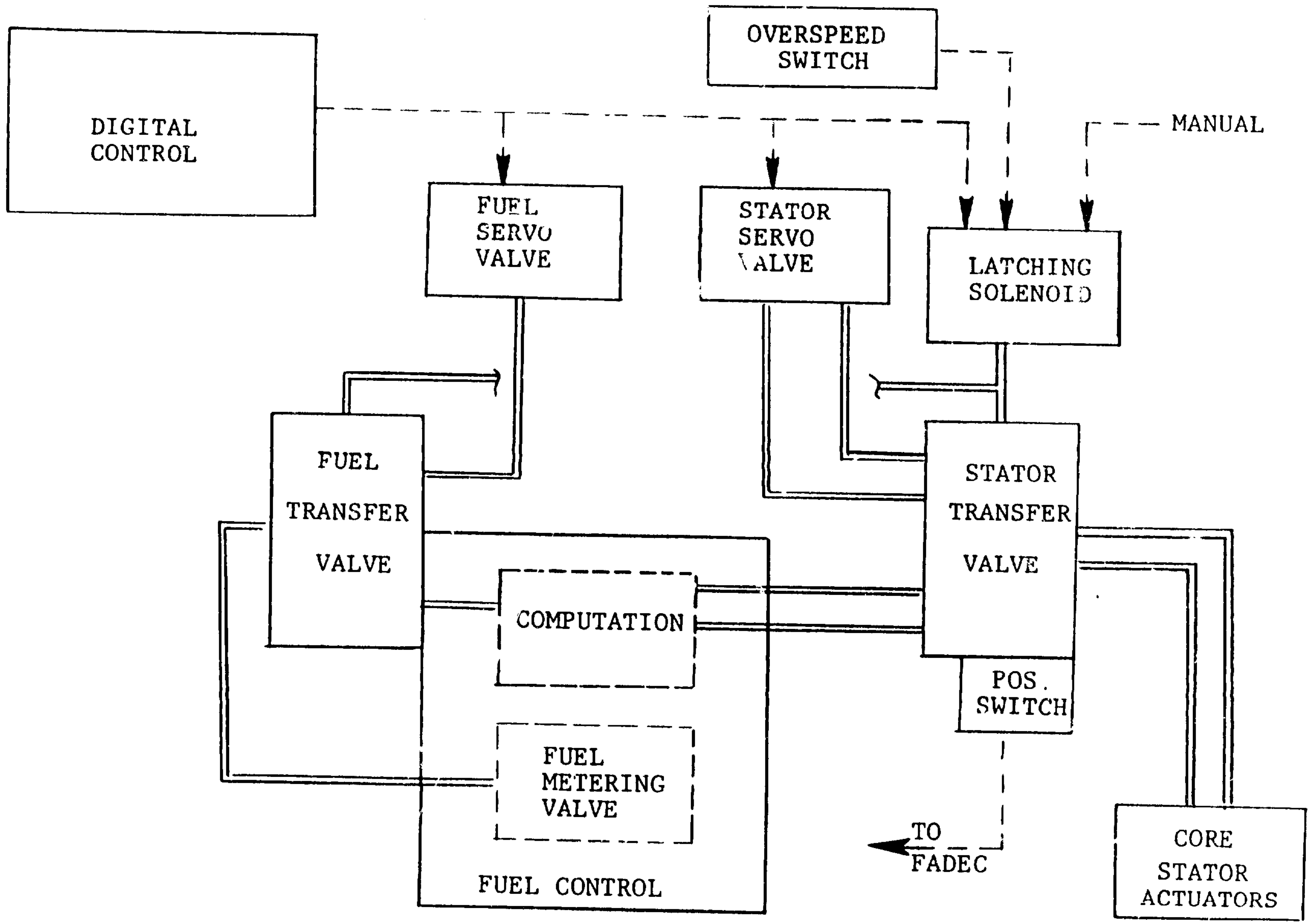
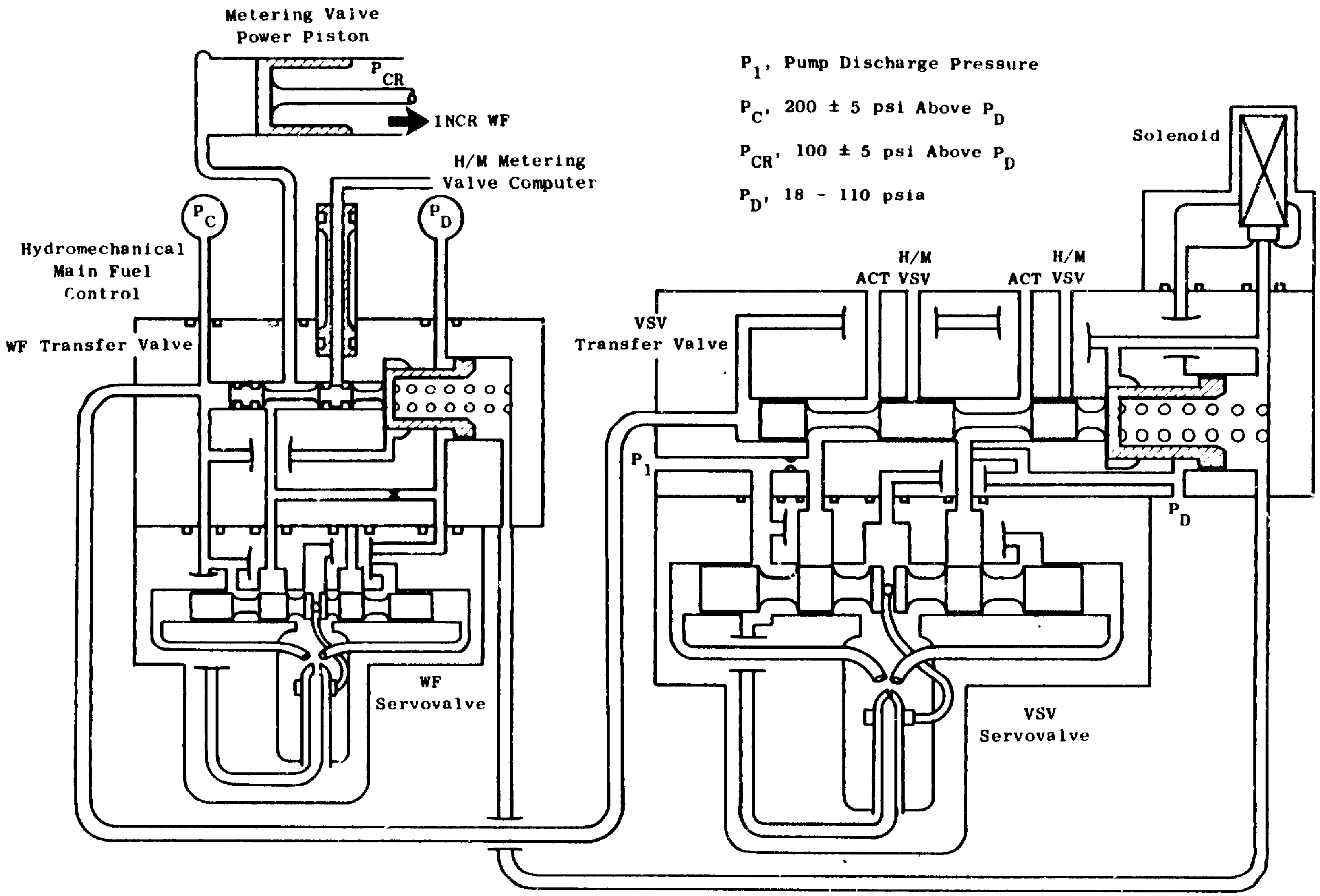


Figure 36. Hydromechanical Backup Control System.



• Valves Shown in Primary Mode

Figure 37. Transfer Valves.

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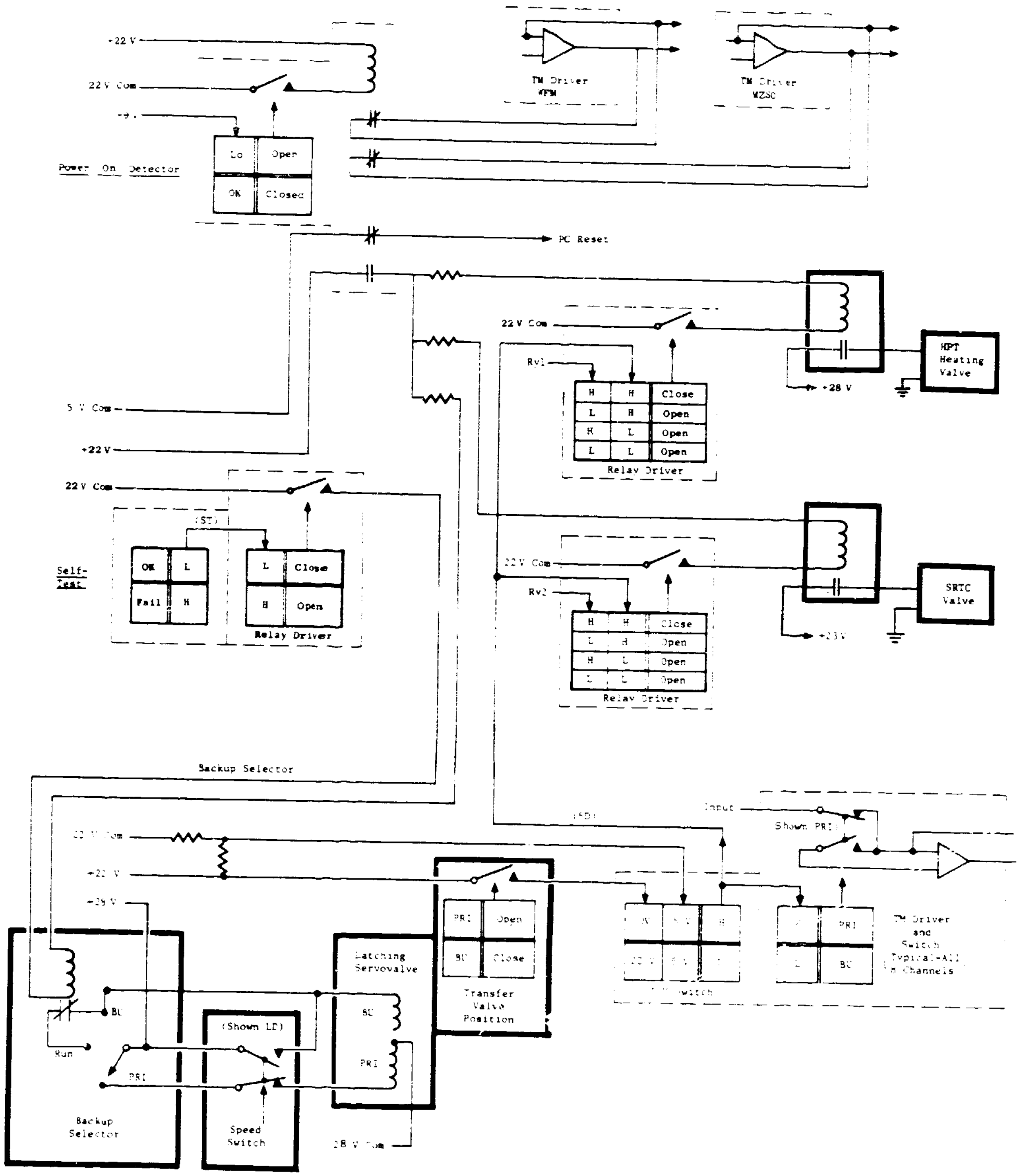

Figure 38. Fail-Safe and Backup Functions.

feature in the solenoid valve assures that the existing condition, either primary or secondary, is retained until a definite signal is received calling for a mode change.

A selector switch in the control room sets the basic system operating mode (Figure 38). With the selector in the normal position the system will normally be in the primary mode, but it will switch to backup position if (1) the digital control power supply voltage is low, (2) if the digital control self-test computation shows a fault, or (3) if a core rotor overspeed occurs which sends a fuel pressure signal from the fuel control to an overspeed pressure switch. Selector switch positions are also provided that set manual mode only, primary mode only, or existing mode only operation.

10.2 SENSOR FAILURE PROTECTION

The E^3 digital control system incorporates a number of electrical sensors that are necessary for proper system and engine operation. Provisions must be made to accommodate occasional sensor failures without significant operational effect. This could be done with sensor redundancy, but this adds cost, increases maintenance activity, and requires additional mounting provisions on the engine. Instead, the computational capability of the digital control is utilized to provide the equivalent of sensor redundancy without multiple sensors by employing a failure indication and corrective action (FICA) concept.

The basic FICA concept involves the incorporation of a simplified engine model in the digital control software, along with sensor failure detection logic which monitors sensor signals and replaces failed signals with model-generated substitutes. A mathematical filter technique (extended Kalman filter) is used to continuously update the engine model using data from all nonfailed sensors.

Figure 39 is a diagram of the FICA. The engine model, outlined in the center of the diagram, is initialized with sensed inputs. It then continues to compute the state-of-engine variables based on inputs from (1) environmental sensors, (2) the fuel control loop (fuel flow rate of change), and (3) the model/sensor signal comparison through the update matrix. If any of the

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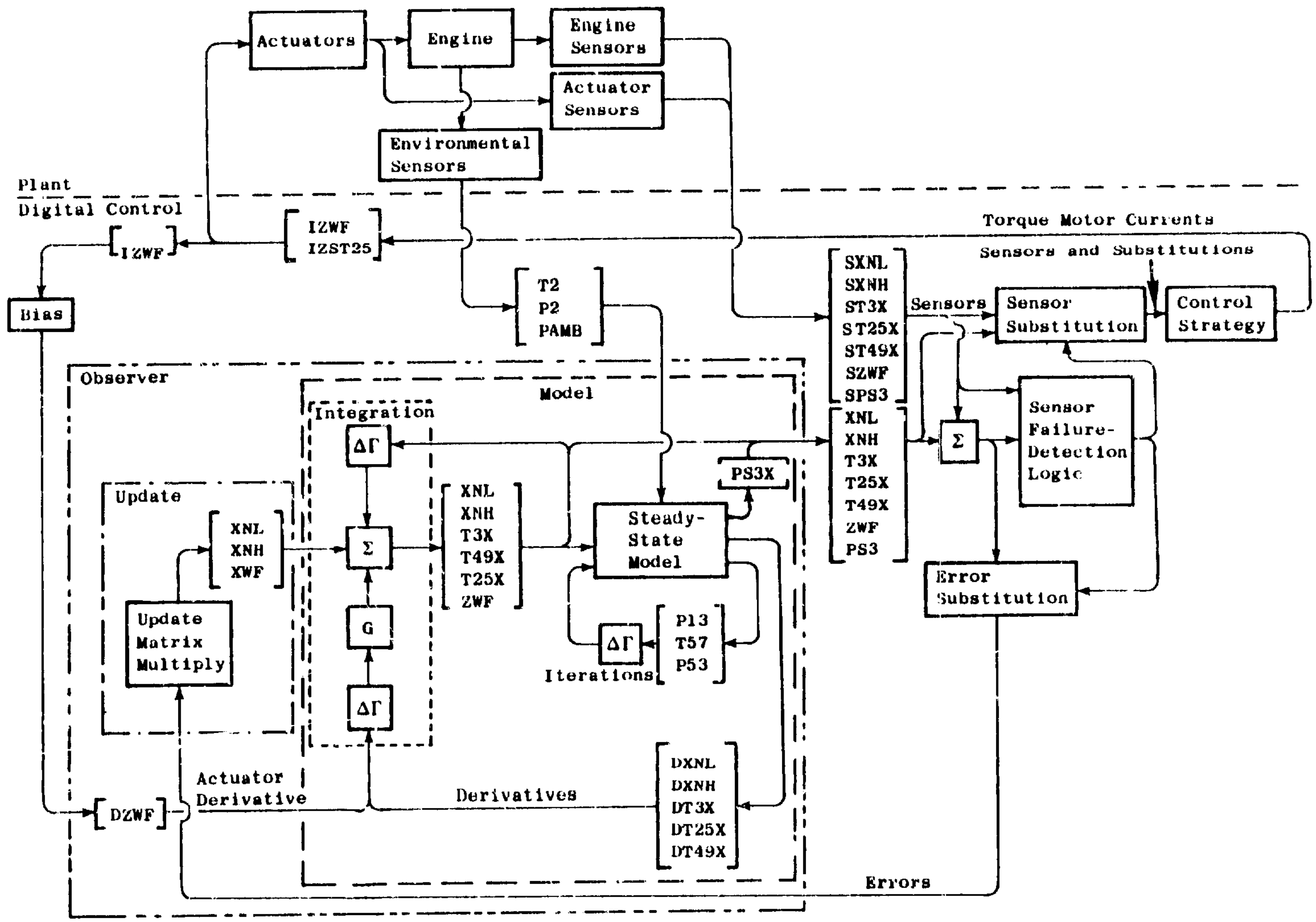

Figure 39. Sensor Failure Indication and Corrective Action.

sensor signals deviate from the equivalent computed state variable by more than a predetermined acceptable amount the computed value is substituted in the control strategy. The error for that variable is eliminated from the update process, and the model continues to compute all state variables with suitable accuracy.

In the E^3 demonstrator engine program the FICA concept will be demonstrated on the ICLS engine. The core engine, which will have a less extensive control system (no LPT-related control and slave controls for core stators), will employ a simpler, out-of-limit strategy for sensor failure protection. When any sensed input is beyond the normal operating range the digital control will take the following action:

Core Speed	-	Indicate self-test failure, switch to backup mode
Core Inlet Temperature	-	Substitute value from manual T25 potentiometer on operator panel
Compressor Discharge Temperature	-	Substitute value calculated from core speed and inlet temperature
Compressor Discharge Pressure	-	Substitute value calculated from core speed and ambient pressure (as indicated by potentiometer)
Exhaust Gas Temperature	-	Substitute value calculated from core speed and inlet temperature
Casing Temperature	-	Set associated value at maximum clearance position
Start Bleed Position	-	Set control output to zero, valves close.
Compressor Clearance Valve Position	-	Set control output to zero, valve goes to maximum clearance position.
Turbine Clearance Valve Position	-	Set control output to zero, valve goes to maximum clearance position.
Main Zone Shutoff Position	-	Set control output to zero, valve opens.

Fuel Metering Valve Position - Indicate self-test failure, switch to backup mode.

Power Lever Position - Switch to backup mode.

These out-of-limit functions will also be included in the ICLS control system for use if the non-FICA mode is selected.

The E^3 digital control also includes provisions for responding in a safe manner to certain fuel valve position sensing failures that result in large errors within the normal operating range. (Loss of certain electrical connections to the fuel valve position transducer can cause such a failure.) The control monitors rate of change of fuel valve position and, when it detects a rate in excess of the normal maximum rate that persists long enough to indicate it is not caused by random electrical noise, it switches to the backup mode. In this way, it protects against a sensor failure that could cause an inadvertent and excessive rise in fuel flow.

11.0 SYSTEM COMPONENTS

11.1 DIGITAL CONTROL

11.1.1 General Description

The E^3 digital control is a full authority digital electronic control (FADEC) designed for operation of the integrated core/low spool (ICLS) configuration of the E^3. It is engine mounted and air cooled. For normal operation, electric power is provided by the engine-driven alternator. For engine starting, and in the event of alternator failure, power is provided from the airframe (test cell) 28-volt bus.

The control is housed in a rectangular chassis with four mounting feet, one located at each corner, to support the chassis to the attaching points of the engine frame. A two-sided cold plate separates the chassis into two compartments. The multilayer ceramic modules are mounted on the cold plate in the shallow compartment. The discrete modules are mounted to the cold plate in the deep compartment. Cooling air flows through the finned passage separating the two mounting sides of the cold plate. Electric interface with the control is through seven wall-mounted electrical connectors. Two air pressures are piped to the control and penetrate the chassis wall to the module pressure sensors/transducers. Housed within the control chassis are 5 multilayer ceramic modules, 16 discrete potted modules, 1 relay, and 8 adjustment potentiometers.

A partition wall in the deep compartment metallically shields the power supply functions from the remainder of the control to eliminate electrical noise interference. All wires between the compartments penetrate the shield only through suitable EMI (electromagnetic interference) filters.

The digital control accepts inputs from inside and outside the control system. The outputs control signals to the control system as a function of control system strategy which is programmed into the control. Inputs and outputs are shown on Figure 40.

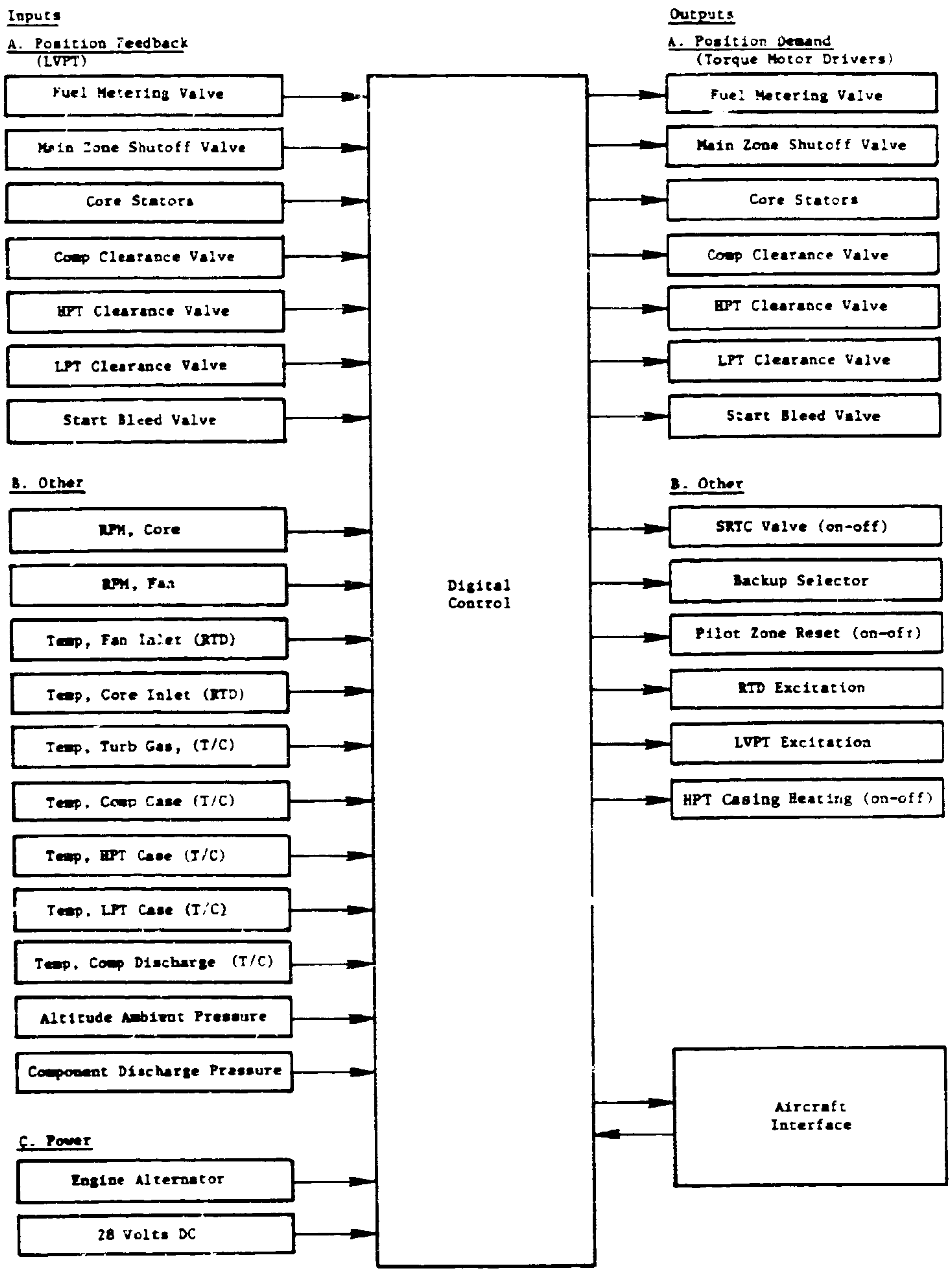

Figure 40. Digital Control - Inputs and Outputs.

The simplified schematic (Figure 41) shows the input/output section, the processor section, and the miscellaneous section. The input/output section includes the 16-bit buffered data bus (BD-bus) as its data path to the central processor. Digital information is passed from the inputs onto the BD-bus through the tristate buffer to the data bus (D-bus). Digital information is also passed from the D-bus through the tristate buffer onto the BD-bus and into the output circuits. All data transmission is done under control of the central processor and on a timesharing basis.

The processor section consists of an address bus (AD-bus) and a D-bus. All data information into and out of the control will pass over the D-bus and into the processor. And all destination information will pass over the AD-bus and will determine the source or destination of data present on the D-bus.

The miscellaneous section contains a linear variable phase transducer (LVPT) excitation driver, a crystal control clock oscillator, and an alternator-driven power source with a 28-volt d.c. power source as a backup.

The digital control provides the computational capability for the selected control system. All of the control law programs, signal conditioning, data processing, and input/output capabilities needed to provide the desired engine operation and interface with the sensors and actuation components are included in the control.

11.1.2 Microprocessor

The central processing unit (CPU) is based on an array of four 4-bit microprocessors cascaded to handle the 16-bit word. This is a fully parallel machine operating at 3.5 MHz clock rate. Figure 42 shows a simplified block diagram of the 4-bit slice AMD 2901 microprocessor used in the control. Features of this processor are (1) special purpose, (2) fractional, (3) two's complement, 4 quadrant, (4) microprogrammed, (5) 3.5 MHz clock rate, (6) 64K word program memory addressing capability, (7) 512-word RAM size, (8) 64-instruction repertoire, (9) 16-bit word size, and (10) low-power Schottky TTL logic family.

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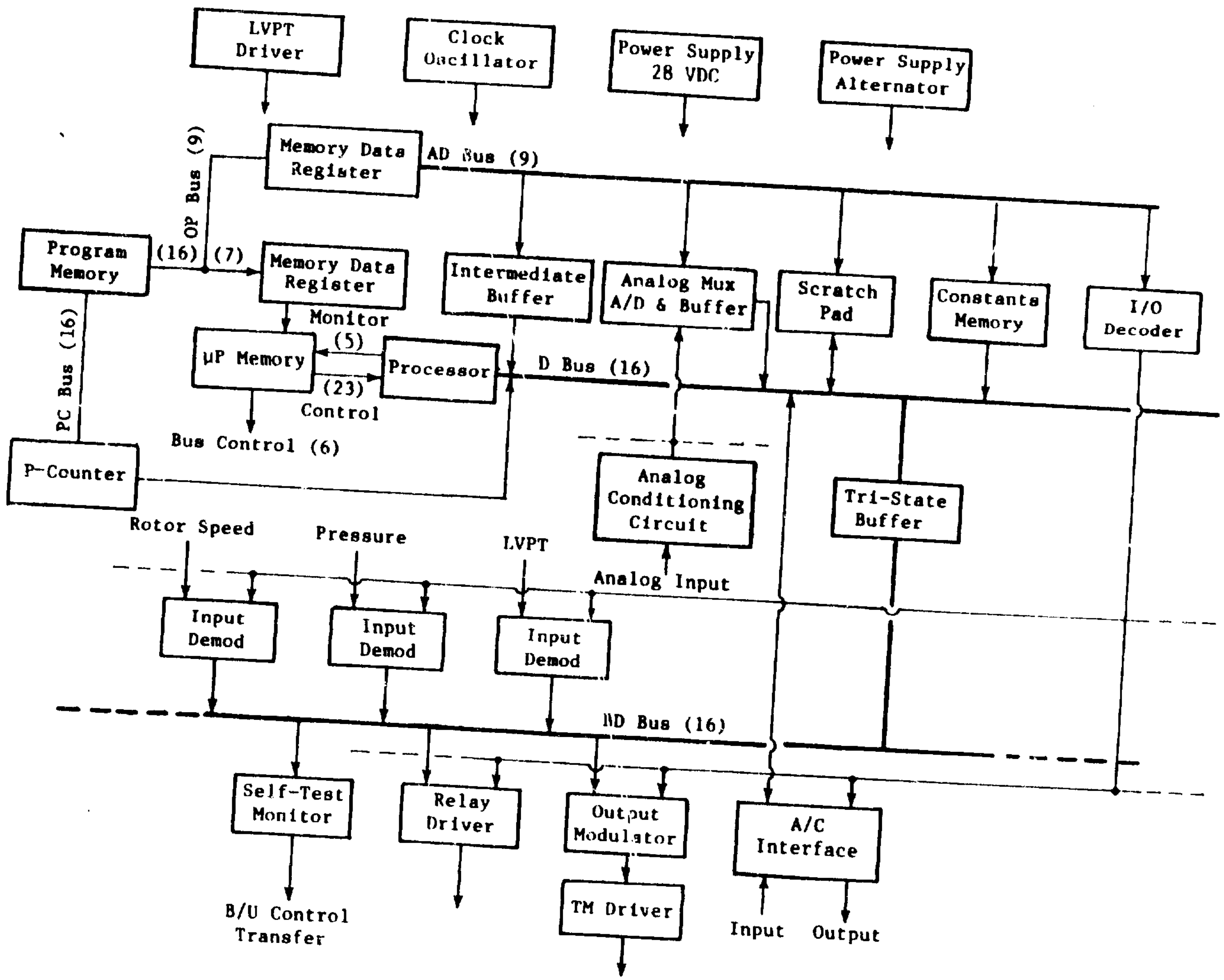

Figure 41. Digital Control Schematic.

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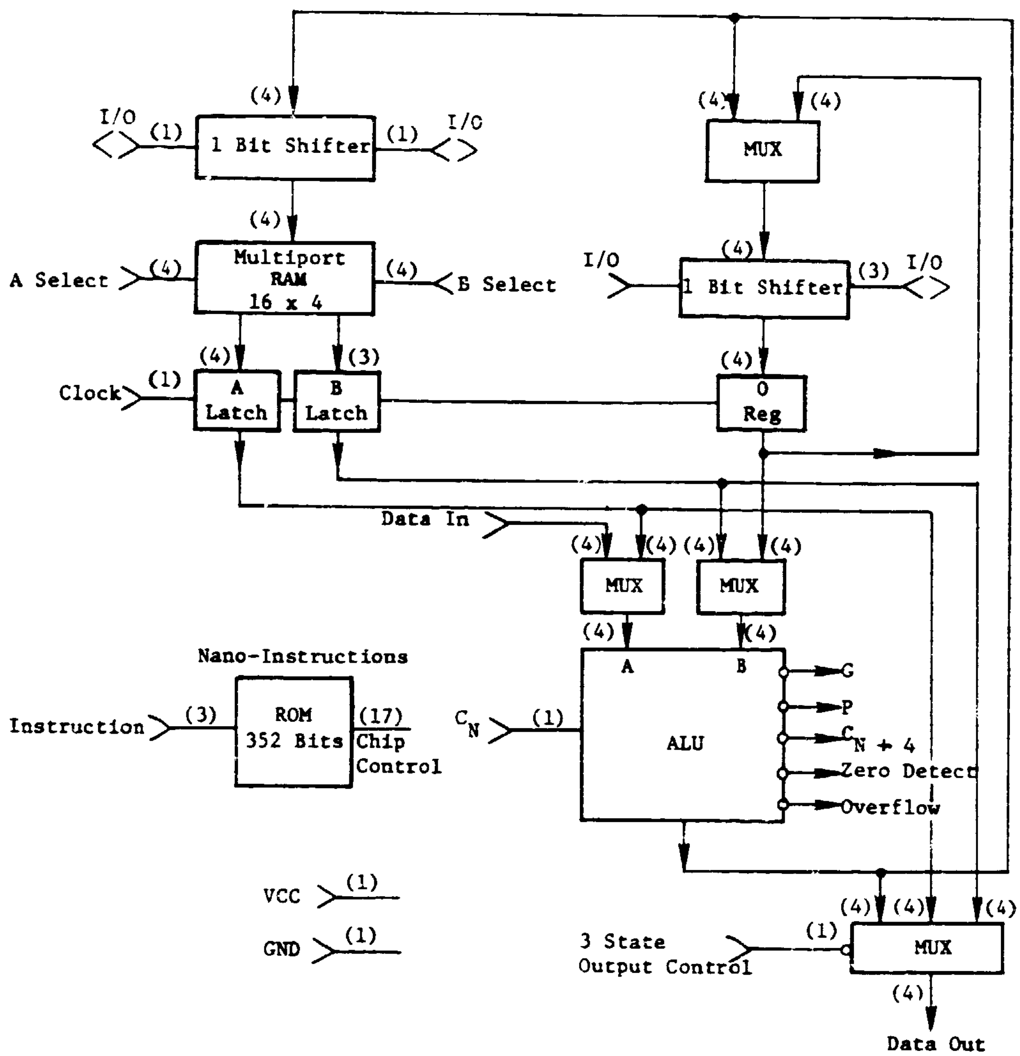

Figure 42. AMD 2901 Microprocessor Block Diagram.

This processor is microprogrammable which enabled its design to be tailored for this engine control application. Such tailoring makes it a special-purpose machine. This 16-bit machine computes algorithms using fractional arithmetic in two's complement notation and has 64 microinstructions which include:

- Input, output, and an address strobe instruction
- Load instructions from various sources
- Add and substract instruction of different locations
- A store instruction that places data in a specified location of read/write memory
- A four-quadrant multiply and divide instruction
- Register exchange instructions
- Magnitude with limit instruction
- Various limited instructions to prevent data overflow
- Right- and left-shift instructions
- Selector instructions that select the most positive or negative data from various sources
- Logical instructions including AND, OR, EXCLUSIVE OR, NOT, and COMPLEMENT
- A number of jump instructions including jump to subroutine and return.

The instruction set functions microcycle information. Mnemonics are listed in the Appendix.

11.1.3 Memory

11.1.3.1 General

Requirements for the digital control memory resulted in partitioning into four memories: program memory, constants memory, scratch pad memory, and microprocessor memory.

11.1.3.2 Program Memory

The program memory uses programmable read-only memory (PROM) integrated circuits, and includes a list of instructions representing the control laws to be executed by the processor. This control architecture and strategy software is arranged in sequential order of execution. The program memory is located in the multilayer ceramic module (MCM) HB8 (A18 module) in the control. The module includes 16K of memory capacity, although this E^3 program is expected to require no more than 8K of memory.

11.1.3.3 Constants Memory

The constants memory is a 1K nonvolatile memory (PROM) that is maintained separate from the program memory. It is used to store constant values used in the control calculation. The constants memory is located in the discrete module A9 and is mounted on a wire-wrapped circuit board so that values in the constants memory can be changed without affecting the program memory.

11.1.3.4 Scractch Pad Memory

The scratch pad memory is used for temporary values during the calculation process as the program is executed; it is a 0.5K random access memory (RAM) having read/write capability. Each location is available for input and retrieval of data. This RAM is located in the digital processor MCM HB6 (A16 module).

11.1.3.5 Microprocessor Memory

The microprocessor memory is the repository for the processor instruction set. This is a read-only memory (ROM), accessed by the microprocessor during execution of the control program. The ROM is located in the digital processor module HB6 (A16 module).

11.1.4 Description of Module Functions

11.1.4.1 General

Partitioning of the digital control circuitry for incorporation into the on-engine control was done to utilize existing MCM's. Three of these MCM designs are from the original Navy FADEC program. These are the A14A, A14B, and A15 modules. The other two MCM's (A16 and A18) were designed for the F404-F1G1 program and incorporate features aimed toward improved life and reliability. Because the circuitry included in these MCM's fixed, the rest of the control circuitry was partitioned to adapt to these existing modules. Functional descriptions of each module follows in sequence of the module identifying number (Figure 43).

11.1.4.2 Module A7

This module includes the isolation transformers used for the 12 signal lines from the aircraft interface simulator (AIS). There is a high, a low, and a groundline for each of four signals: data, clock, transmit, and receive. This metallically shielded module houses the coupling transformers for each of the 12 signal lines.

11.1.4.3 Module A8

Module A8 houses the two pressure transducers and a temperature-sensing integrated circuit. These are digital-type sensors in which force is applied to a quartz crystal proportional to sensed air pressure. The resonant frequency of the quartz crystal is proportional to the applied force and to the sensor temperature. The output signal from the pressure sensor is the crystal resonant frequency. The temperature-sensing integrated circuit provides an output voltage proportional to pressure sensor temperature. Control program software includes equations to modify the sensed pressure signal as a function of the pressure sensor temperature.

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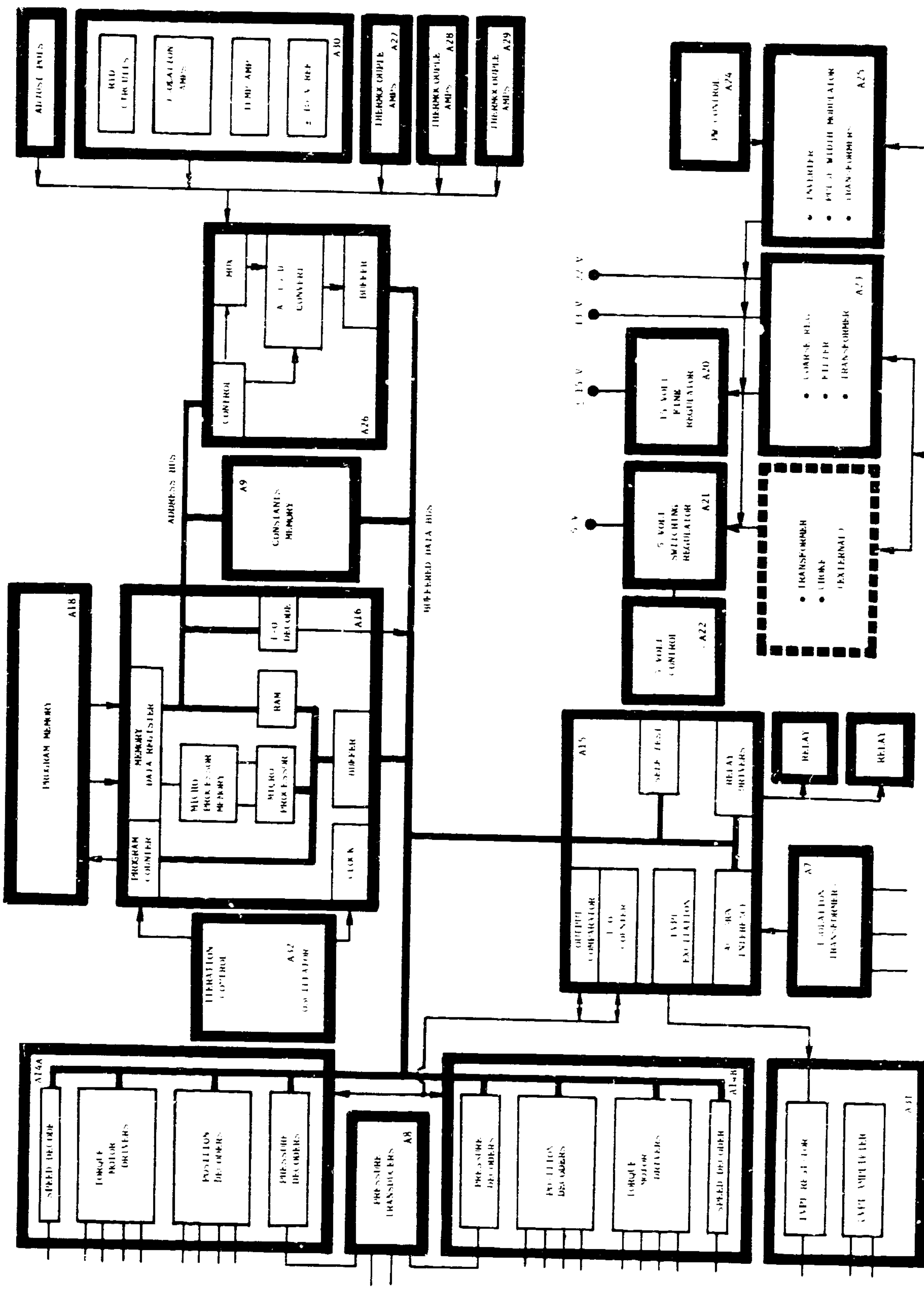

Figure 43. Digital Control Partitioning - On Engine Unit.

11.1.4.4 Module A9

This is a digital discrete module which contains the constants memory. It consists of one wire wrap circuit board with four PROM dual inline packages (DIPS) mounted to it. This module is mounted on the cold plate in the shallow compartment of the control. The address bus is input to the constants memory and data is output to the buffered data bus. This memory can be changed without affecting the program memory.

11.1.4.5 Modules A14A and A14B

These are two identical multilayer ceramic modules identified also as HB4A and HB4B. The modules incorporate the control input/output functions. The channel assignments have been made for use of the several channels on each module and the use of more than one module, and the system software is written to match the channels as wired. Each of the modules includes the following functions:

1. One engine speed decoder circuit comprising a zero crossing detector, counters, and latches to measure the time between the zero crossings of the input signal and enters that time on the buffered data bus.

2. Four torque motor drivers that are power amplifiers operating in response to the output modulator. This is used to connect digital outputs from the central process into demand torque motor currents. The torque motor current is established by the length of the "on" time of the driver amplifier. These four channels of torque motor drivers are identical hardware and can be used to operate any of the control loops. The channel assignments have been made and the software is created to match for proper system control. By supplying either ±10-volt d.c. or only +10-volt d.c. to the driver circuits, the driver can be used for either the "fail-safe" servovalve (in the fuel valve control) or for the "standard" servovalve (in the air valve controls).

3. Four position decoder circuits comprising a zero crossing detector, counters, and latches to measure a phase difference from the linear variable phase transformer (LVPT) and to input the digital value on the buffered data bus. The phase difference is proportional to the position of the controlled variable as measured by the LVPT.

4. Two pressure decoder circuits comprising counters and latches to measure the frequency output from the pressure transducer and to input the digital value onto the buffered data bus.

11.1.4.6 Module A15

Module A15 is a multilayer ceramic module, also called HB5. This module is known as the interface module, but it includes other noninterface functions.

1. The aircraft multiplexer (MUX) interface function is included and provides a compatible connection between the AIS signals (such as data, clock, transmit and receive) and the buffered data bus. Pilot or control room control of the engine is through this data path.

2. Linear variable phase transformer (LVPT) excitation is provided by this module. Two module-mounted PROM's are programmed to generate sine waves, one 90° out of phase with the other. These two sine waves are then provided to each LVPT in the control system. The LVPT is wound such that the phase of its output signal, as compared to the base sine wave, is proportional to the position of the LVPT slug.

3. There are three relay driver circuits that operate to close a solid-state switch when commanded by the central processor through the BD-bus. The closed switch provides power to the specified relays. One of the relay drivers is used to activate the backup selector unit to switch engine control over to the backup control. A second relay driver is used to operate the start range turbine cooling air valve.

4. There is a self-test circuit included on this module which operates to compare a test word from the data bus to a hard-wired reference. In the event they are different, a signal is sent to the relay driver which operates the backup selector unit.

5. The input/output counter and torque motor modulator are located on this module. These counter functions are used by all of the speed, pressure, LVPT decoders, and by the torque motor drive circuits located on the two A1 modules.

11.1.4.7 Module A16

This is the digital processor module. It is an MCM of a new configuration compared to the A14 and A15 MCM. The A16, also known as HB6, incorporates an improved pin-out arrangement and a welded-on cover for improved life and reliability. This module includes the following central processor functions:

- A microprocessor comprising four 4-bit-slice integrated circuits cascaded to provide a 16-bit machine. The AM 2901 is used.

- A microprocessor memory that holds the system instruc[illegible] set.

- The clock frequency divider and distribution is provided by this module.

- The random access memory (RAM) is incorporated to provide the scratch pad memory used during program execution.

- The program counter (P-counter) is included in this module and is used to walk the system through the program memory locations during the execution of the program.

- A tristate buffer is included to interface the data bus off this module for connection to other modules.

11.1.4.8 Module A18

This is an MCM similar in configuration to the A16 module. The A18 (HB8) incorporates the program memory in PROM chips, size 1K by 8. There are 32 PROM's arranged to give 16K of 16-bit words. This program memory interfaces with the A16 module through the P-counter and the operation code busses.

11.1.4.9 Module A20

Module A20 is a conventional printed circuit board, a potted module that includes circuitry to provide the regulated 15-volt power used throughout the control. A zener diode provides the reference and an op-amp operates through staged transistors to hold the output voltage proportional to the reference. This provides the regulated +15 volts. The -15 volts is controlled similarly, except that the op-amp tracks the +15 volts rather than the zener reference. The input to this regulator is ±22 volts.

11.1.4.10 Module A21

This is a discrete module that includes circuitry to provide for the fine regulation of the 5-volt power supply. Input to this module is from the engine-

C-2

driven alternator as coarse-regulated and rectified by a separately packaged (outside the control) transformer, choke, and diodes. A compatible alternator would negate the need for this separate coarse regulation.

Input to the A21 module is at approximately 9-volts d.c. The module includes the following functions:

1. Primary switching shunt transistor, controlled by the primary control circuit in module A22 to hold 5 volts.

2. Backup switching shunt transistor, which is controlled by the backup control circuit in module A22 to hold 5.2 volts in the event the primary regulation circuit fails in the direction of high voltage.

3. A filter circuit comprising 2 chokes and 16 capacitors to smooth the regulated 5 volts for use by the digital circuits.

4. Diodes to permit connection of the alternator-supplied regulated 5 volts and the 28-volt-d.c.-supplied regulated 5 volts, such that loss of alternator supply allows automatic takeover by the 28-volt system.

11.1.4.11 Module A22

This module is a conventional printed circuit board discrete module which includes the control circuitry for the A21 switching shunt 5-volt regulator. An integrated circuit device contains the 5-volt reference and controls a low-power transistor, which in turn controls the shunt transistor (in A21 module) to hold the regulated voltage proportional to the reference. As discussed in the preceding section, there are two such circuits: one to regulate at 5 volts and one to regulate at 5.2 volts.

11.1.4.12 Module A23

This is a discrete module that includes circuitry to provide for the regulation of the ±3 volts and 22 volts d.c. Input to this module is from the engine-driven alternator using a different set of windings than that used for the module A21. The module includes the following functions:

- A mag-amp regulator is used to control the output voltages of the tapped transformer. This is done by using a feedback winding on the power transformer in order to provide control current to the mag-amp.

- There are 8 diodes arranged to give full wave rectification of the ±13- and 22-volt output from the power transformer. There are 12 capacitors arranged to provide suitable smoothing and filtering of these voltage outputs.

- An additional winding on the secondary of the power transformer provides the signal used by the control for core rpm measurement.

11.1.4.13 Module A24

Module A24, a discrete module, includes two printed circuit boards comprising the circuitry used to control the dc-dc converter and the pulse width regulator. Circuits residing in module A24 provide the following functions:

1. The dc-dc converter control circuit includes an integrated circuit oscillator; its output operates two stages of control transistors. Output of the control transistors is used to operate the power switching transistors in module A25 to convert the input 28-volt d.c. to a.c. for input to its power transformer.

2. The pulse width regulator control circuit includes an integrated circuit oscillator whose output operates two stages of control transistors. Output of the control transistors is used to operate the power switching transistors in module A25. This control circuit senses the fine volt bus voltage and operates to control the "on" time of the power transistors to regulate at slightly less than 5 volts.

11.1.4.14 Module A25

This discrete module includes the transformers and power transistors used to provide regulated 13 and 22 volts d.c. and regulated 5 volts d.c. when supplied with 28 volts d.c. The power transistors are controlled by the circuitry included in module A24 and described above. The following functions are included:

- The dc-dc converter circuit includes the power transformer with tapped secondaries to provide the 13 and 22 volts. These feed through the eight diodes arranged to give full wave rectification of the ±13 and 22 volt outputs from the power transformer. The 28-volt d.c. input is converted to alternating current by the cycling power transistors and is then input to the primary winding of the power transformer.

- The pulse width regulator circuit includes the power transformer with a tapped secondary to provide 5-volt output. The 28-volt d.c. input is converted to alternating current by the cycling power transistors and next input to the primary winding of the power transformer. The fine regulation of 5 volts is accomplished by varying the "on" time of the power transistors.

11.1.4.15 Module A26

A26 is a discrete module that includes two printed circuit boards incorporating circuitry to receive d.c. signal level voltages onto the MUX, convert these voltages to a digital word, and place the digital word onto the buffered data bus. The following functions are included:

1. Two 16-channel MUX's and associated control functions are included. The FADEC address bus operates through the MUX control to sequentially select the channel to be output from the MUX through a buffer amplifier and input to the A-D converter.

2. The A-D converter, its control functions, and its precision voltage reference are included. When an analog voltage output from the MUX is input to the A-D converter, the control function initiates "start convert" after sufficient time has elapsed for the signal voltage to stabilize at its final value. The converted digital word is then output to the tristate buffer and, when signaled, is placed on the BD-bus.

3. The precision voltage reference included in this module for the A-D converter is used as input to buffer amplifier circuitry, located in module A30, to generate the ±10-volt reference voltages for use throughout the control.

11.1.4.16 Modules A27, A28, and A29

The three modules are identical except for calibration. Each is a discrete module including two identical printed circuit boards. Each printed circuit board includes circuitry for one thermocouple amplification function. The three modules, therefore, include a total of six thermocouple circuits. Each thermocouple amplifier circuit comprises the following:

- Cold junction compensation is provided by the "gumdrop", a balco wire-wound coil that has resistance in proportion to the temperature and the chromel-alumel junction physically adjacent to the coil. This varying resistance provides a calibrated bus to the thermocouples input to the Stage 1 amplifier.

- Two stages of amplification are provided so that the output from the circuit is a 0 to -10 volts d.c. signal proportional to the thermocouple-measured temperature. This output signal voltage from each printed circuit board of each module is input to the specified channels of the MUX's located in module A26. From there it is transmitted to the BD-bus.

11.1.4.17 Module A30

This is a discrete module comprising two printed circuit boards: one includes six amplifier circuits, the second board includes six amplifiers. The function of each is listed below.

1. There are five gain-of-one isolation amplifiers. Each can accept a 0 to 10-volt d.c. input and provides an isolated output of 0 to -10 volts d.c. These signals are next input to the designated MUX channels described in Section 11.1.4.15 and then on to the BD-bus as a digital value.

2. There is a pressure transducer temperature (PTT) amplifier that monitors the output of the AD 590 temperature sensor chip located in the pressure transducer module (module A8). Output of this amplifier also is a 0 to -10 volts d.c. proportional to the temperature in the A8 module. This voltage is input to the specified MUX channel.

3. There are two resistance temperature detector (RTD) amplifiers that monitor the resistance change of the two RTD sensors, one located at the fan inlet and one at the core inlet. Output of these are 0 to -10 volts d.c. proportional to the resistance change of the RTD which is proportional to the two sensed temperatures. This voltage is input to the specified MUX channel.

4. There are two RTD excitation circuits which provide the constant current excitation to the two RTD's.

5. There are two gain-of-one amplifiers. One is used to generate the plus and one the minus 10-volt d.c. references used throughout the control. Input to these amplifier circuits is -10 volts d.c. from the precision reference chip located in module A26.

11.1.4.18 Module A31

Module A31 is a discrete module that includes two printed circuit boards. Included are several miscellaneous analog circuits, as follows:

1. The LVPT excitation resistors are included in this module. For each LVPT, each of the excitation signals passes through one of the 400-ohm resistors. The module incudes 20 such resistors, but the E^3 control uses only 14.

2. The power "on" detector circuit and the relay controlled by this circuit are included. In the event that the 5-volt power is not in regulation, such as during startup without the 28-volt supply or a complete power loss during operation, the following actions occur:

- Short the main fuel valve torque motor driver output to give a zero output signal (close fuel valve).
- Short the main zone shutoff valve torque motor driver output to give a zero output signal (open MZSO valve).
- Reset the program counter to zero.
- Reenergize the coil of the relays for the backup selector unit and the start range turbine cooling valve. This results in a switch to backup control and closing the S' air valve.

3. There are two LVPT amplifiers included; each provides amplification of an LVPT output signal in order to be compatible with the zero crossing detector. The control system includes two short LVPT's which have output signal levels too low and, therefore, must be amplified.

4. There are two speed circuit amplifiers which are used to make steeper slope signals at the zero crossing to assure compatibility with the zero crossing detectors. The core speed and the fan speed signals each use one amplifier.

11.1.4.19 Module A32

This module is a discrete module including one printed circuit board. The clock oscillator and the iteration control circuitry are included in this module.

11.1.5 Physical Configuration

11.1.5.1 General

The digital control circuitry was partitioned as shown in Figure 43 and as described in the preceding paragraphs. This partitioning was based on using available MCM's. Three of the MCM's were developed under the Navy FADEC program during 1978-1980. Two newer MCM's are currently being developed for a military engine-mounted electronic control unit. The remaining circuitry, which is not included on the five MCM's, was partitioned in a logical functional arrangement as follows:

Function	No. Modules
Power Supply	6
Pressure Transducers	1
Isolation Transformers	1
Clock Oscillator, Iteration Control	1
Constants Memory	1
Analog-to-Digital	1
Thermocouple Amplifier	3
LVPT Excite and Amplifier	1
Isolation amps and RTD Excite	1
Total	16

11.1.5.2 Chassis Design

The chassis design is shown in Figures 44 and 45. The final design uses a two-sided air-cooled cold plate separating the box into two compartments: one for the MCM, one for the discrete modules. The cooling air flowpath is through a single layer of fin stock arranged for flow across the width of the box instead of along the length. This gives a larger flow area and a shorter flow distance. Provisions are included for wiring across the cold plate assembly.

The cold plate assembly includes two plates separated by the fin stock airflow passage. The plates are thick enough to accommodate the many threaded inserts required for the device holddown screws. All of the modules and devices are attached to the plates by means of these holddown screws. And all of the modules and devices can be installed or removed by fasteners on their mounting side of the respective cold plates. These thick plates provide a flat mounting surface for the modules to assure maximum heat transfer. The thicker plates also provide improved flatness to assure nearly 100% fin stock

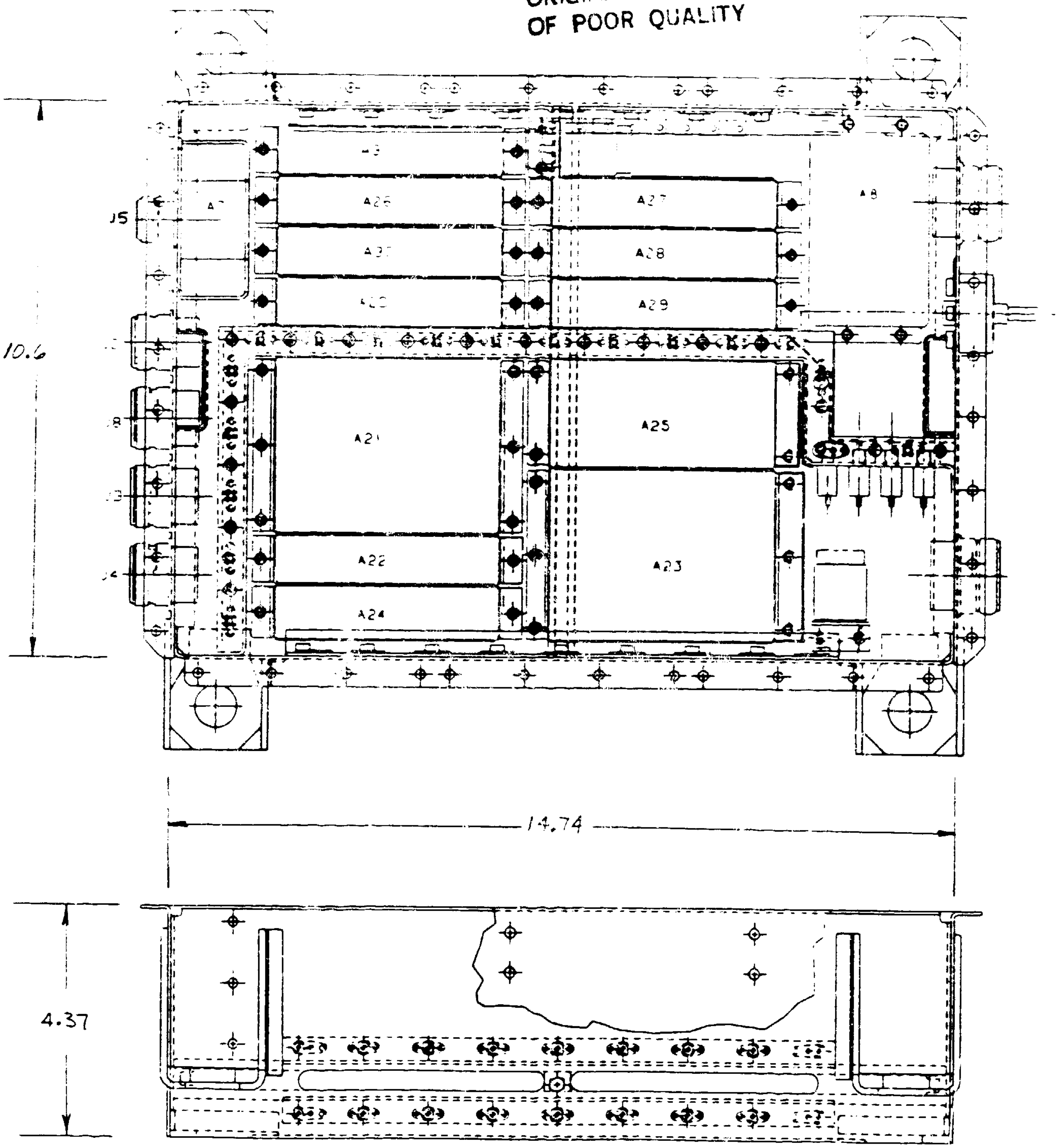

Figure 44. On-Engine Digital Control, Standard Module Side.

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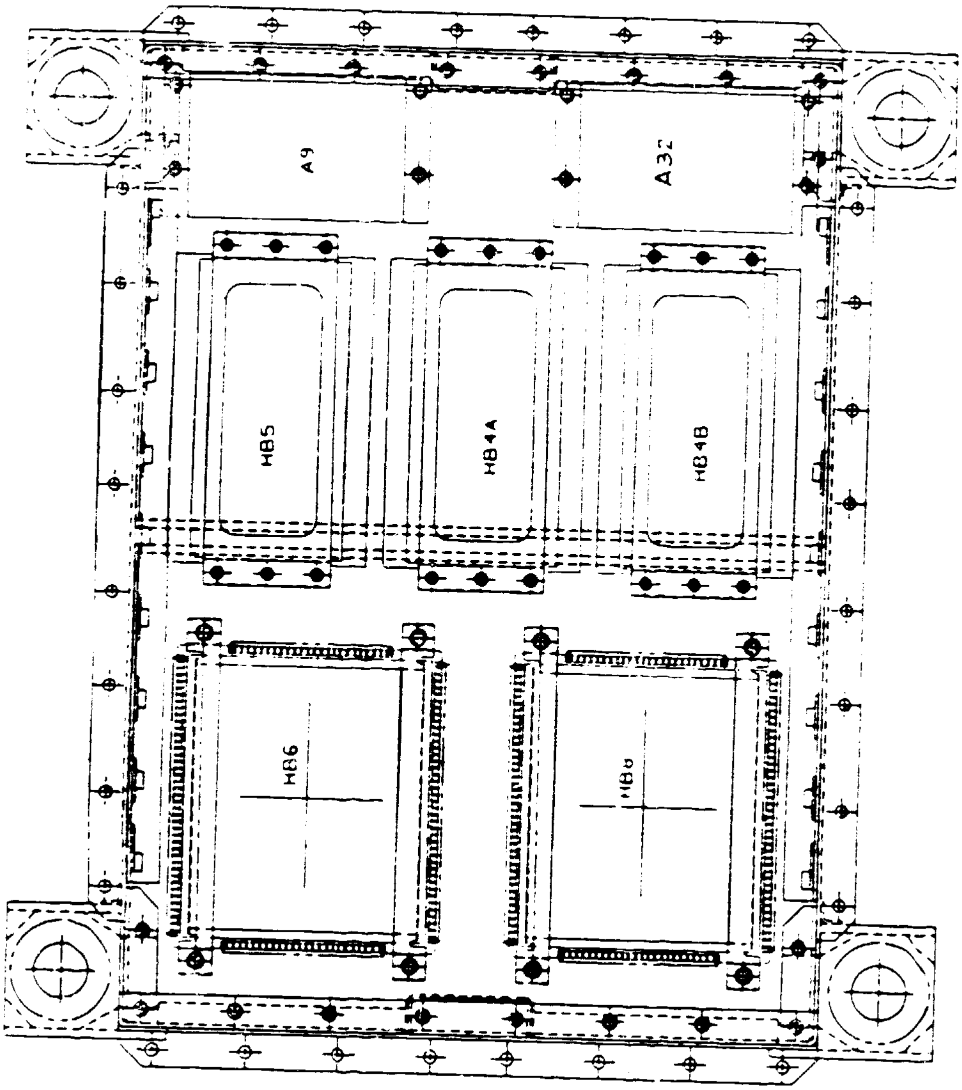


Figure 45. On-Engine Digital Control, Hybrid Module Side.

braze attachment to the plates. The circuit partitioning was completed, giving consideration to the discrete module size. This chosen arrangement resulted in all of the discrete modules having two common dimensions (except the pressure transducer and the isolation transformer modules). All of the discrete module housings are the same height, the same length, and of identical construction. Only the width is larger for the power supply module housings in order to contain larger devices such as transformers, chokes, filter capacitors, and diodes. This similarity of module housing size provided significant design cost savings, not only in the housing design but particularly in the many printed circuit board designs.

11.2 ALTERNATOR

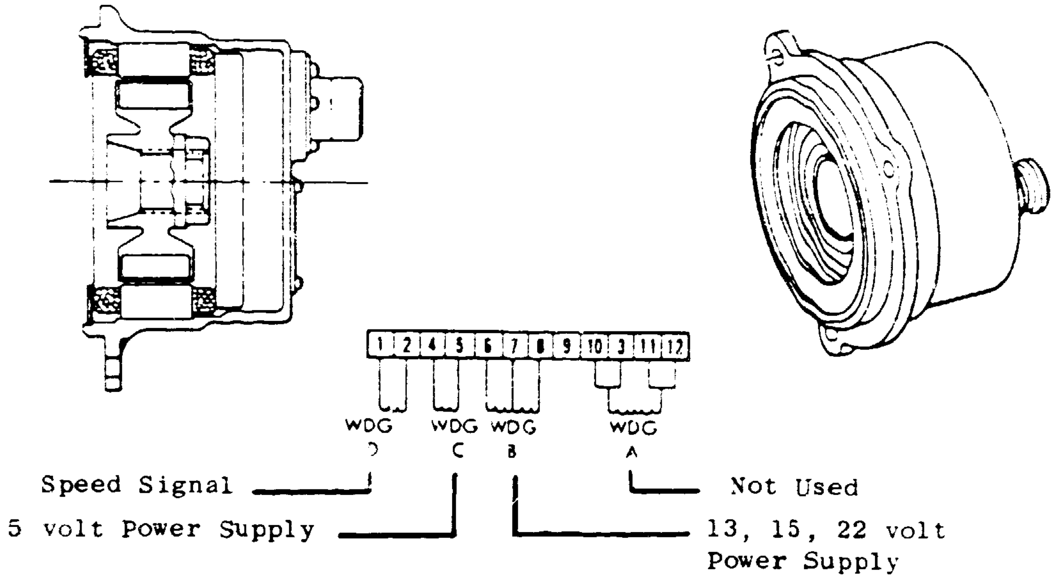
The control alternator provides electric power to the digital control and a core signal for the cockpit or test cell readout. This is an F101 control alternator. The alternator is engine-gearbox mounted and driven with the rotor attached to the gearbox output shaft. Figure 46 shows the electrical schematic and cross sections of the unit. For this application, three of the four windings are used.

The design characteristics of the control alternator are listed below.

- Configuration — Four windings; Six pole pairs; Permanent magnet type
- Drive — 25,302 rpm at takeoff power
- Output frequency — 0.1 times drive rpm

Output Power

Winding	% N	Volts	Amps
B	15	24.3-39.8	0.72-0
	85	26.8	1.3
	115	0-308	1.81-0
C	15	10.4-16.3	3.0-0
	100	69.4	3.0
	115	0-122	6.35-0
D	10	5.78	0.002
	100	57.8-74.7	0.02-0
	115	0-86	6.18-0



Electrical Schematic

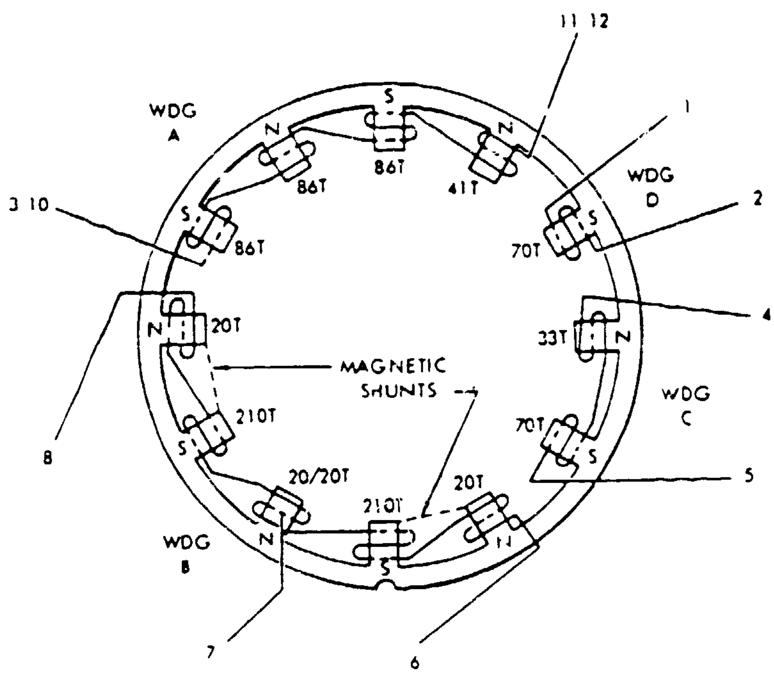


Figure 46. Control Alternator.

11.3 SERVOVALVES

Figure 47 shows a schematic of a "fail fixed" electrohydraulic servovalve. This is typical of the servovalves used in control of three of the engine functions; that is, main fuel flow, core stator control, and main zone shutoff. The remaining controlled functions, such as pilot zone reset, start bleed control, and three clearance control loops, use the "standard" type electrohydraulic servovalves. The principal difference between the two types of servovalves is in the characteristics of the flow versus milliamp input relationship. These servovalves include a torque-motor-operated jet pipe first stage and a spool valve second stage.

For the "fail fixed" servovalve, the input current is between zero and 100 milliamps and output flow is as follows:

- Up to 8 mA = Zero output flow
- Between 8 and 50 mA = Flow from C1 port
- Between 50 and 92 mA = Flow from C2 port
- Above 92 mA = Zero output flow

For the "standard" servovalve, the input current is between -80 and +80 mA and output flow is as follows:

- From -80 to 0 mA = Flow from C2 port
- At zero mA = Zero output flow
- From 0 to +80 mA = Flow from C1 port

The design characteristics of the electrohydraulic servovalves are listed in the following:

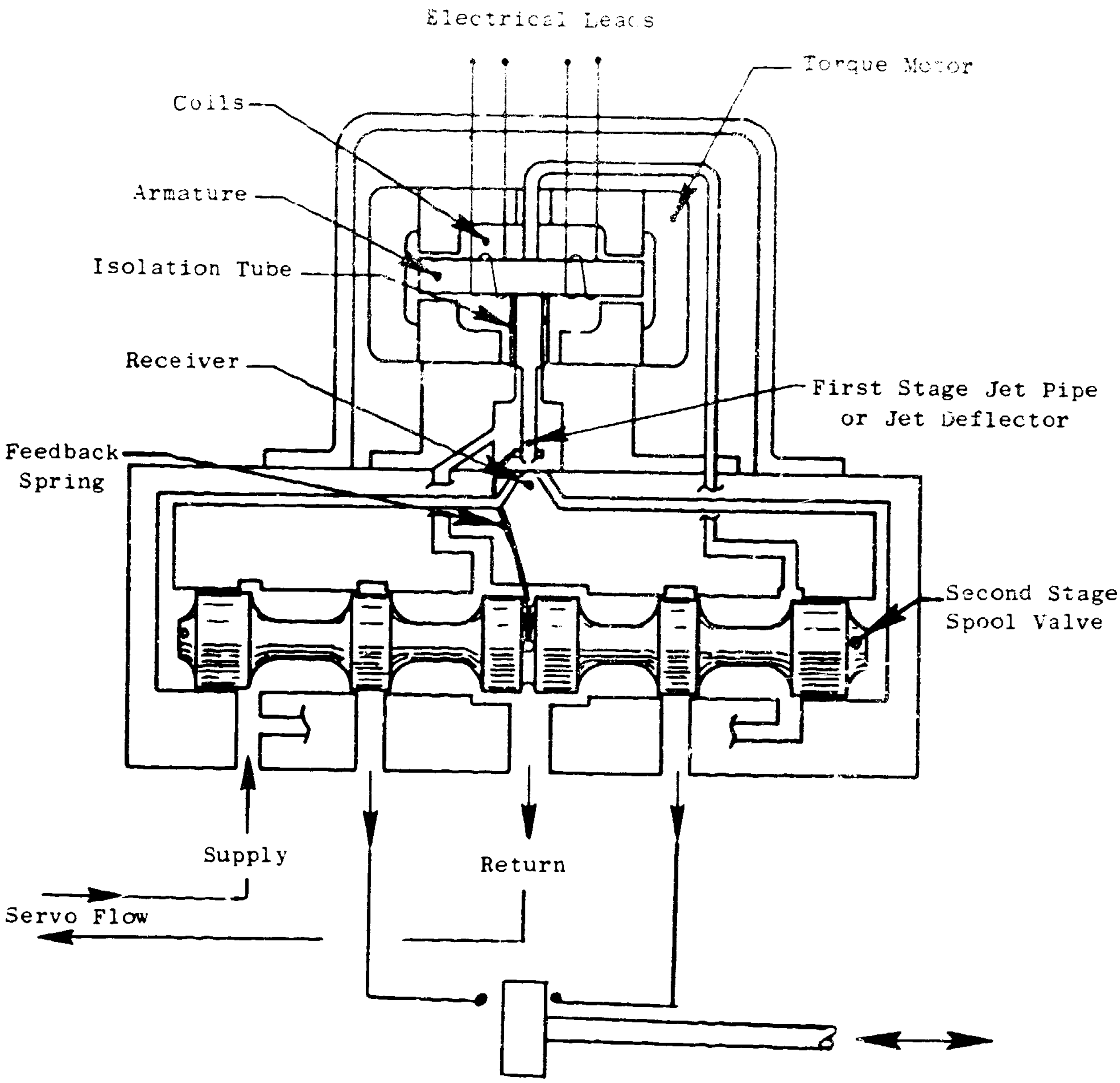


Figure 47. Typical Electrohydraulic Servovalve.

	Fail-Safe	Standard
Number of coils	2	2
Connection	Parallel aiding	Parallel aiding
Rated current	100 mA	+80, -80 mA
Maximum current	200 mA total 110 mA either coil	220 mA total 110 mA either coil
Resistance, d.c.	15 ohms per coil	29 ohms per coil
Coil matching, d.c. resistance	Within 10% of other	Within 10% of other
Resistance, a.c.	300 ohms max	300 ohms max.
Apparent inductance	180 MHz pos max. 40 MHz neg max.	180 MHz pos max. 40 MHz neg max.
Input wave shape	Unipolar square wave	Unipolar square wave
Input frequency	427 Hz	427 Hz
Variation	Pulse width modulation	Pulse width modulation

11.4 POSITION TRANSDUCERS

11.4.1 Linear Variable Phase Transformer (LVPT)

Figures 48 and 49 show examples of two of the LVPT's used for the E^3 control system. The LVPT produces an output voltage whose phase changes proportionally with the position of the core. The transformer utilizes four primary coils which are wired in alternately connected, out-of-phase pairs. The two pairs of primaries are connected to a two-phase, 427-Hz source having 90° of phase separation. The four coil sections then represent phases of 0°, 90°, 180°, and 270°. A moveable core positioned along the axis of the transformer will couple the flux of several primary coils into the secondary coil where the flux vectors are summed to produce an output voltage whose phase lags with respect to the reference (0 degrees). The magnitude of the phase lag is proportional to the position of the core with respect to the primary windings.

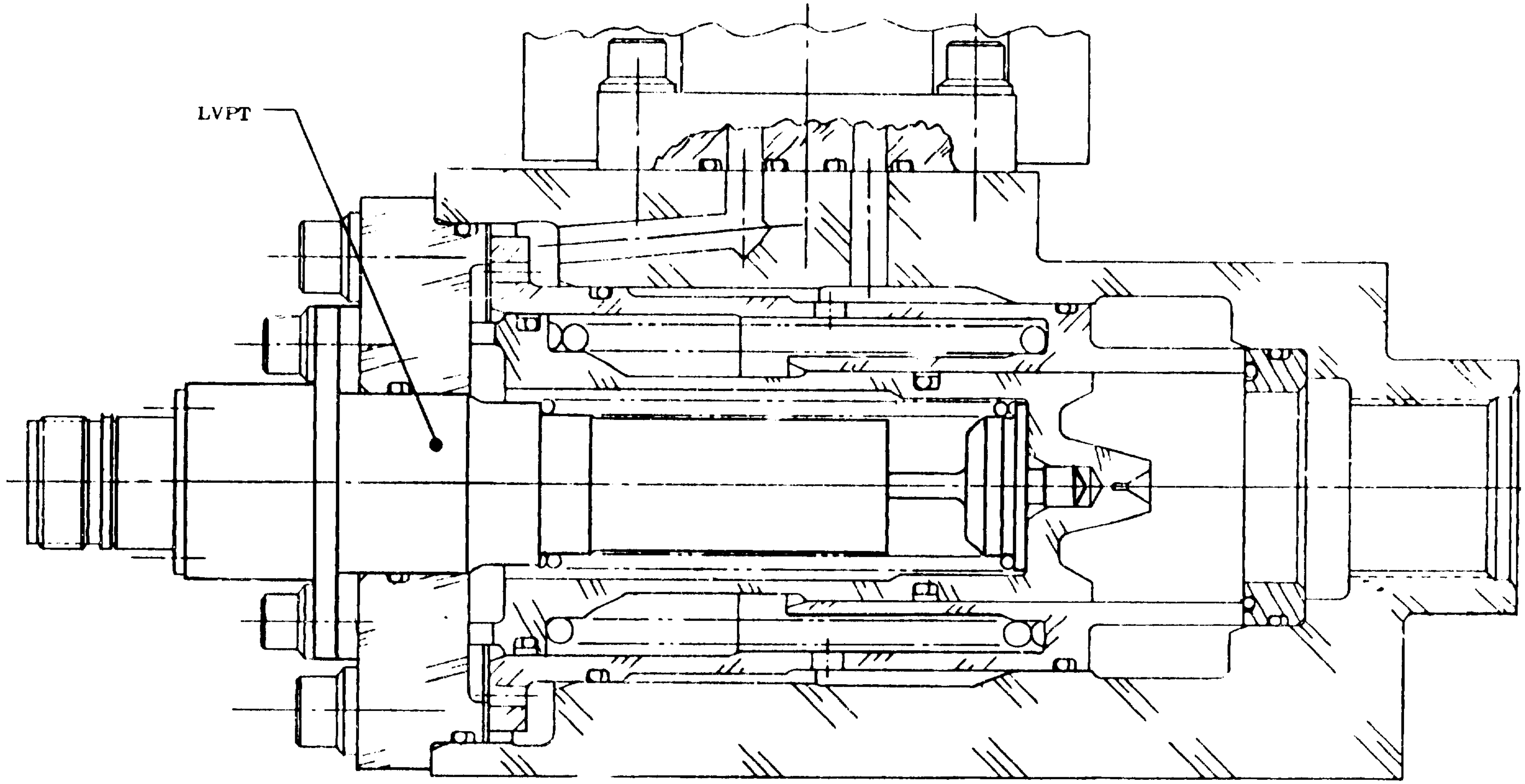


Figure 48. Position Sensor (LVPT) for Main Zone Shutoff Valve.

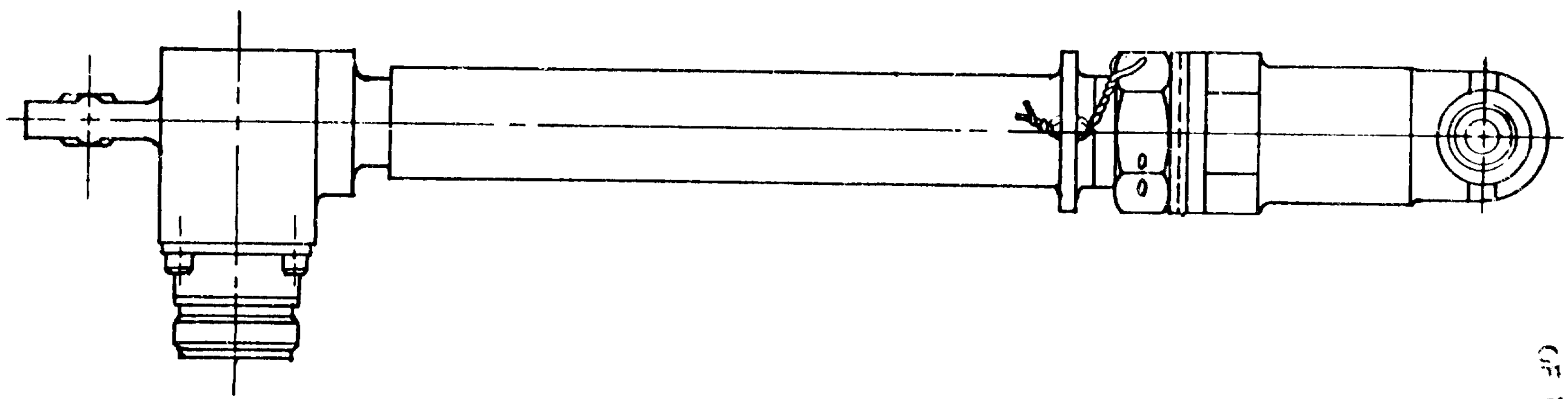


Figure 49. Position Sensor (LVPT) for Compressor Stator Angle.

There are three different lengths of LVPT's used in this system. Each is constructed to give a linear output of 9° to 171° phase difference between the output signal and the reference for full stroke.

11.4.2 Rotary Variable Phase Transformer (RVPT)

Figure 50 shows the RVPT as used to sense the position of the fuel metering valve located in the fuel control. The RVPT is electrically identical to the LVPT. The coils are arranged to be responsive to the rotation of the core. The output is linear between 9° and 171° phase difference between the output signal and the reference for full rotary stroke.

11.5 FAN SPEED SENSOR

An F101 engine fan speed sensor is used on the E^3. The sensor utilizes a self-powered magnetic sensing head consisting of two separate but tandem sensing coils. The two coils provide fan speed signals separately to the engine digital control and to the off-engine (test cell) speed indication. The fan speed sensor is installed so the sensing head is positioned within minimum practical clearance from the toothed target wheel mounted to the fan shaft. The toothed disk has six identical, equally spaced teeth.

11.6 FAN INLET TEMPERATURE (T12) SENSOR

The inlet temperature sensor, Figure 51, measures the freestream air temperature entering the engine. The active element is a small coil of platinum wire which changes electrically as its temperature changes. This resistance temperature detector is mounted on and protrudes through the inlet duct ahead of the fan. The sensor housing is a slotted airfoil with a series of small holes. The action of the airfoil, slots, and holes results in air flowing around the sensor at essentially freestream temperature unaffected by boundary layer conditions. This is the same sensor as used on the F101 engine to sense T2.

The design characteristics of of the T12 sensor are listed as follows:

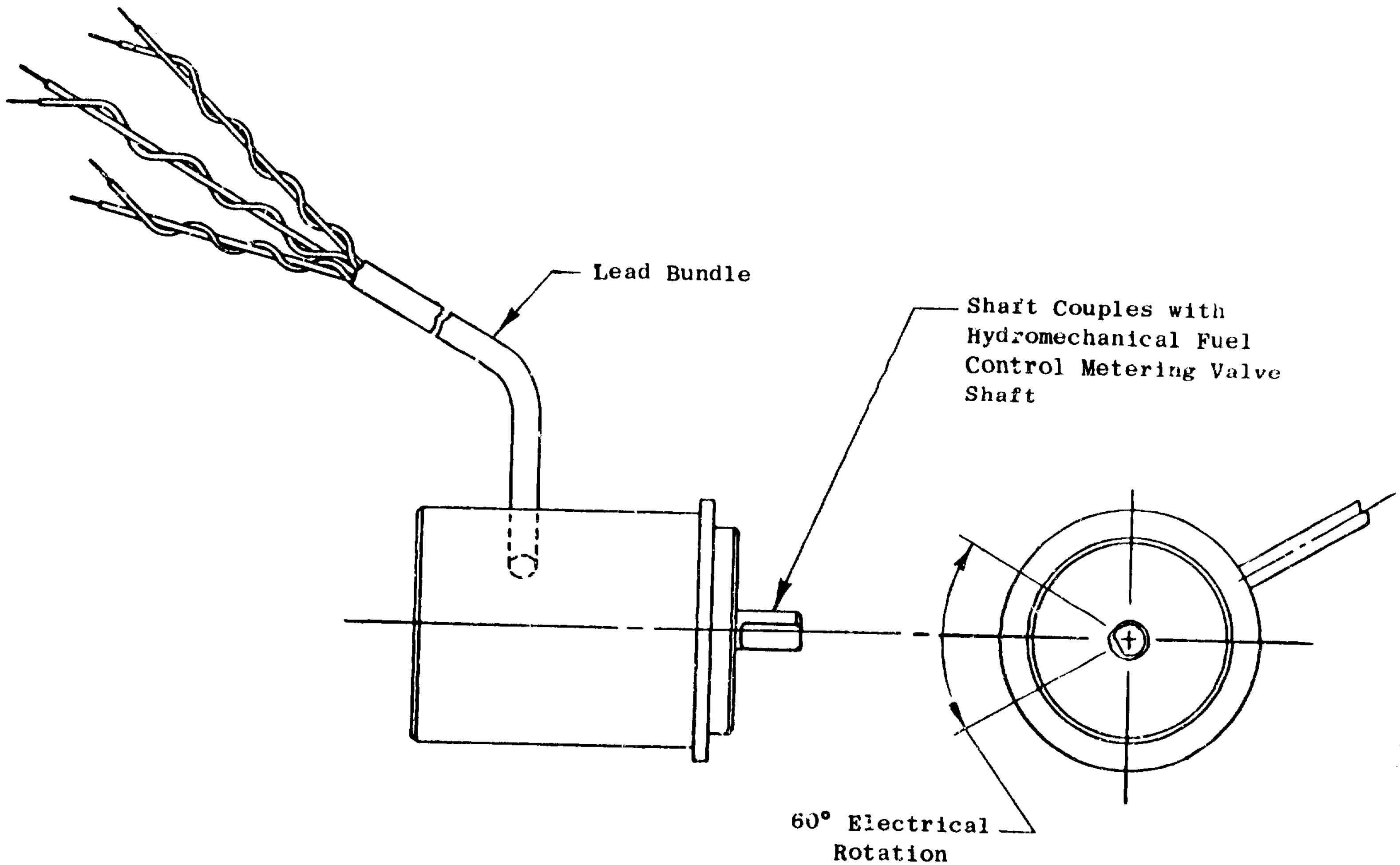


Figure 50. RVPT Metering Valve Position Transducer.

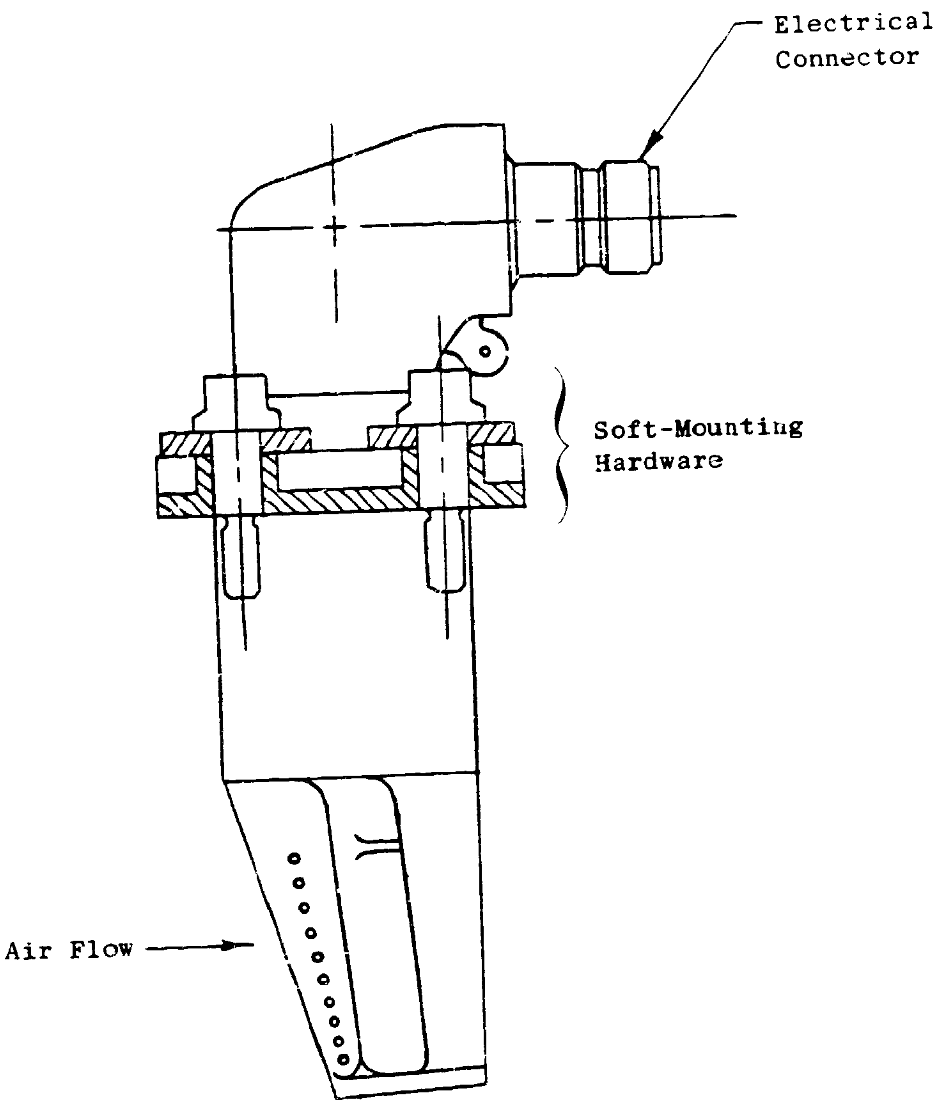


Figure 51. Fan/Compressor Inlet Temperature T_{12}/T_{25} Sensor.

Range	219 to 345 K (-65° to 160° F)
Excitation	Constant 12.5 mA d.c.
Output	Resistance proportional to temperature
Static accuracy	0.3% absolute temperature
Response	6 sec at 4.5 $kg/s/m^2$ (10 $lb/s/ft^2$)
Recovery error	0.5% absolute at 0.4 Mach

11.7 COMPRESSOR INLET TEMPERATURE (T25) SENSOR

The compressor inlet temperature sensor is a resistance temperature detector and is the same part number part as the T12 sensor. This T25 sensor is located in the core compressor inlet duct and operates over a range of 219 to 403K (-60° to 265° F).

11.8 COMPRESSOR DISCHARGE TEMPERATURE (T3) SENSOR

The T3 sensing probe assembly is mounted on the outer combustor casing. This is a chromel-alumel thermocouple similar to a test instrumentation thermocouple probe used on several previous engines. A leadout attachment concept is incorporated to make the probe less susceptible to handling damage. The swaged magnesium-oxide-filled metal sheath in which the thermocouples junction is encased, is led out, looped and spliced into a flexible, metal-covered lead before clamping to the probe housing. Figure 52 shows this T3 sensing probe design.

The design characteristics of the T3 probe are listed as follows:

Range	255 to 1089 K (0° to 1500° F)
Output	Per Mil-W-5846C
Static accuracy	0.75%
Response	2.13 sec at 4.5 $kg/s/m^2$ (10 $lb/s/ft^2$) 0.85 sec at 27.2 $kg/s/m^2$ (60 $lb/s/ft^2$)
Insulation	5 megaohm min. to ground

11.9 TURBINE DISCHARGE (T42) TEMPERATURE SENSOR

HP turbine discharge temperature is sensed by selected chromel-alumel thermocouples in instrumentation rakes immediately behind the HP turbine. Three thermocouple signals from the test instrumentation rakes are connected

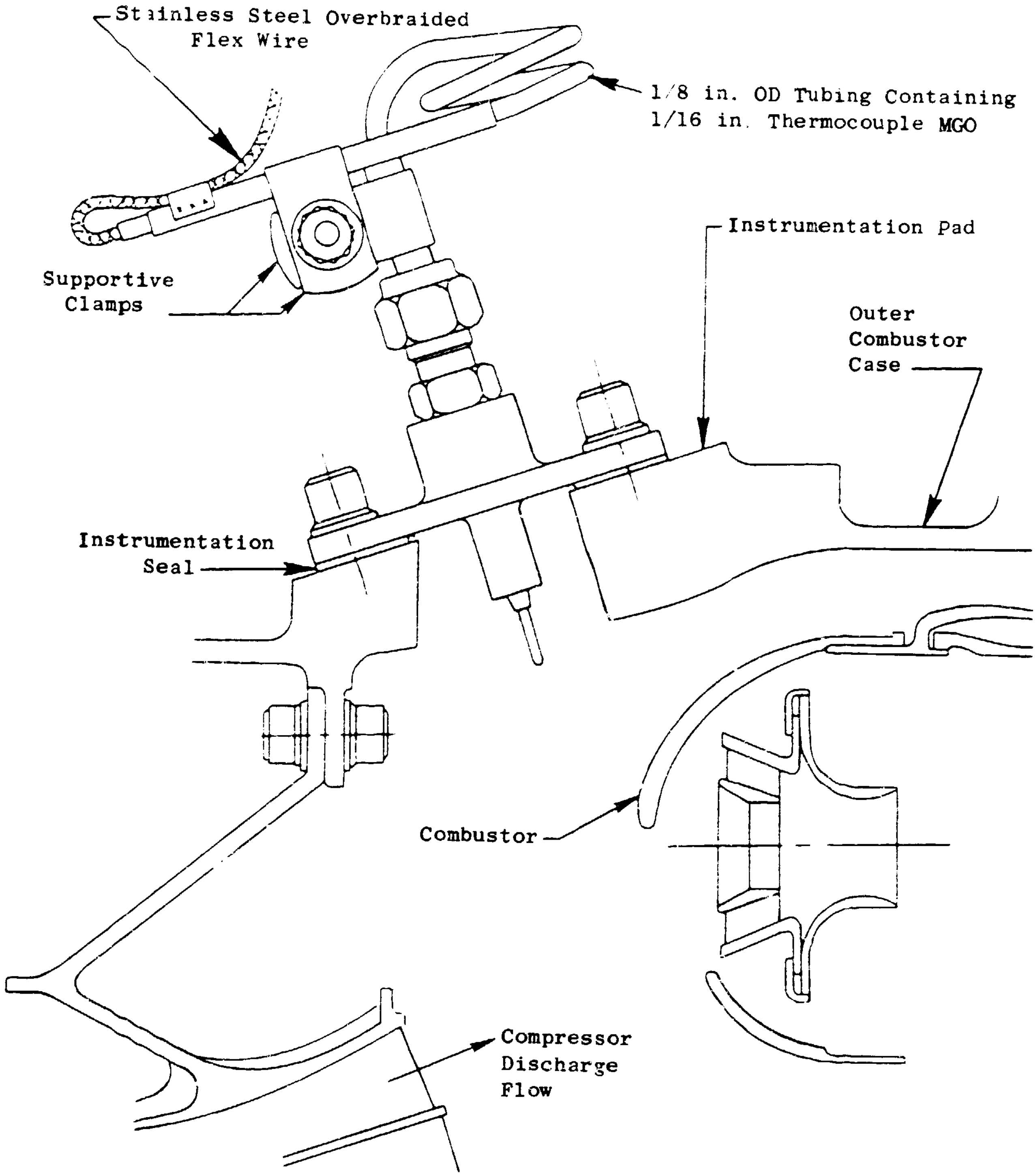


Figure 52. Compressor Discharge Temperature (T3) Seneor.

in parallel and spliced into the control system electric cabling. These three signals are from different radial and circumferential locations and are dedicated to use by the control system.

The design characteristics of the T42 thermocouples are listed as:

Range	478 to 1589 K (400° to 2400° F)
Output	per Mil-W-5846C
Static accuracy	0.75%
Response	4.7 sec at 4.5 $kg/s/m^2$ (10 $lb/s/ft^2$) 1.28 sec at 27.2 $kg/s/m^2$ (60 $lb/s/ft^2$)

11.10 CASING TEMPERATURE SENSORS

For sensing casing temperature, chromel-alumel skin thermocouples are mounted on each of the engine casings being used for clearance control (aft compressor, HP turbine, and LP turbine) for dedicated use of the control system. Three chromel-alumel thermocouples are provided at each location: one for initial use and two for spares. Each of the thermocouples will be spliced into a wiring junction to which the control cabling is attached.

11.11 FUEL CONTROL

This is an F101 control modified to be compatible with the E^3 digital control and to provide for backup control. Figure 53 is a photograph of the conrol.

11.11.1 Control Inputs

The following signals are input to the fuel control:

- Inlet fuel = Discharge flow from fuel pump
- T25 = Fuel pressure differential generated by control and remote sensor
- PS3 = Air pressure signal
- N2 = Input shaft through fuel pump mounting pad
- PLA = Shaft rotation of 130°

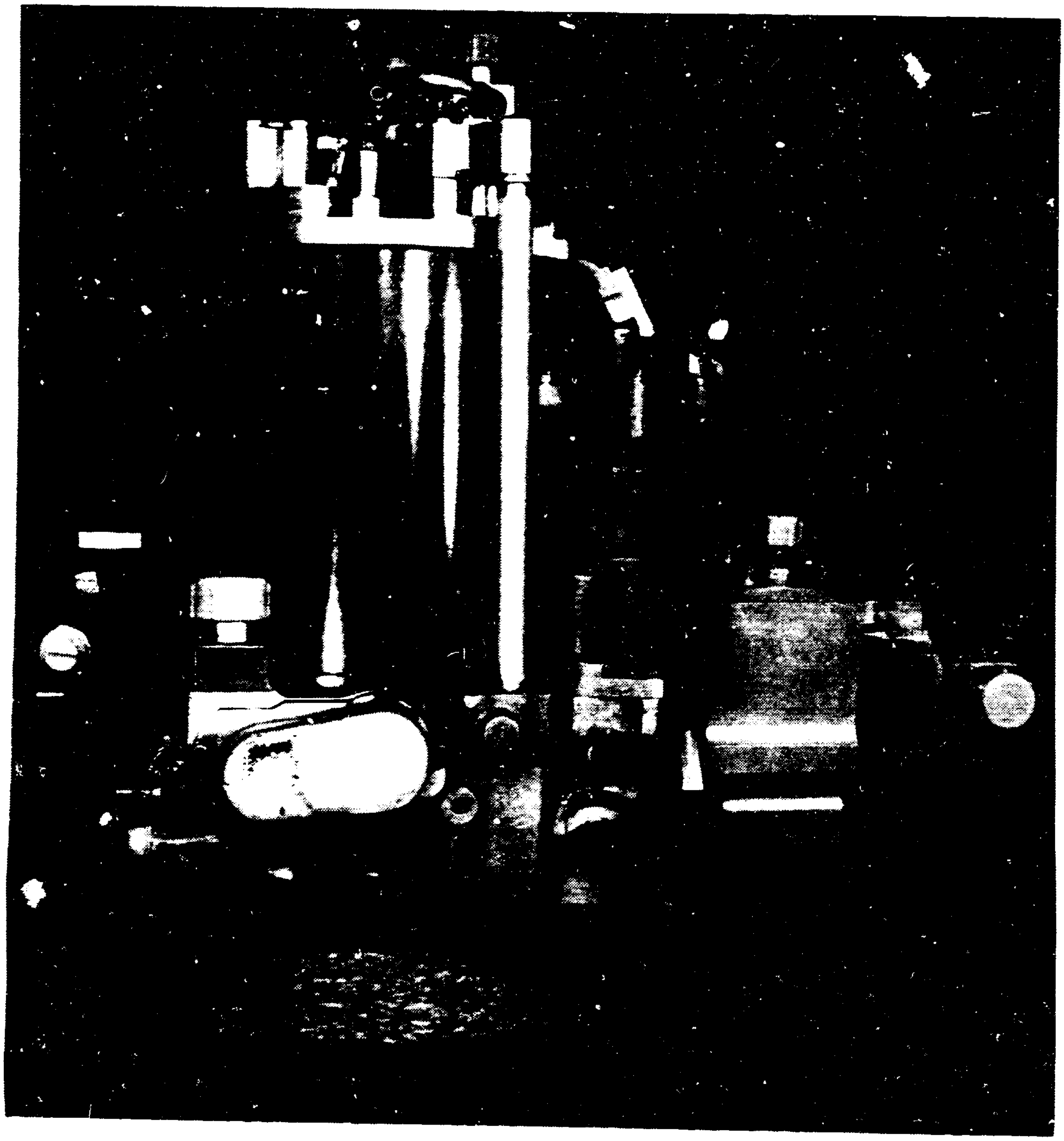


Figure 53. Main Fuel Control.

- Stator Feedback = Linear motion of a flexible cable
- Electrical fuel control signal = An electric signal from the digital control
- Position transducer excitation = Two sinusoidal signals
- Transfer signal = A fuel pressure from the transfer valve

11.11.2 Control Outputs

- Engine fuel = Fuel to the combustor
- Stator actuation flow = Fuel supplied to external ports for actuation
- Bypass fuel = Fuel returned to pump interstage
- Overspeed pressure = Fuel supplied for the overspeed pressure switch
- Transfer supply = Fuel supplied for operation of transfer valve
- External servo supply = Fuel supplied for remote servovalves
- Metering valve position signal = An electric signal to the digital control.

11.11.3 Mounting

The control is mounted on the engine fuel pump which is mounted on the accessory gearbox.

11.11.4 Control of Fuel Flow Primary Mode

In the primary mode, fuel flow to the engine combustor is controlled in response to the electrical fuel control signal from the digital control in accordance with the servovalve characteristics.

11.11.5 Control of Fuel Flow Backup Mode

In the backup mode, fuel flow to the engine combustor is controlled in accordance with N2 (core rpm) governing requirements with various overrides as follows:

1. N2 Governing - N2 is governed in accordance with the schedule percent N2 versus PLA. The maximum speed flat on the schedule is adjustable ±3%. The governor is of the proportional-plus-integral type.

2. Acceleration Limit - Except as limited by the absolute minimum, fuel flow will not exceed the level defined by the acceleration schedule.

3. Deceleration Limit - Except as limited by the absolute minimum, fuel flow will not be less than the level defined by the deceleration schedule.

4. Absolute Minimum Fuel Flow Limit - Set at 90.7 kg/h (200 lb/h) and is internally adjustable between 45.4 and 181.4 kg/h (100 and 400 lb/h).

11.11.6 Overspeed Signal

An external fuel pressure signal is provided which operates a remote pressure switch to cause automatic transfer to the backup control mode if core speed goes above 13,450 (±70) rpm.

11.11.7 Ultimate Overspeed Limit

If core rpm exceeds 13,750 (±70), fuel flow will be cut off within 0.05 seconds and will remain so until control inlet pressure is below the normal minimum as set by the pressurizing valve.

11.11.8 Stator Control

The control includes a four-way valve to control flow to and from the stator actuators through the transfer valve. The high pressure supply to the stator valve is pump discharge flow filtered within the control. The stator valve low pressure return is to bypass return pressure.

11.11.9 Operating Mode Transfer

The fuel control selects between primary and backup modes in response to a fuel pressure signal supplied at the transfer signal port.

11.11.10 Pressurizing Valve

The control includes a pressurizing valve to maintain sufficient inlet pressure for proper control and servovalve operation.

11.11.11 Cutoff Valve

The control includes a valve to cut off the fuel flow and activate the pump unload when PLA is below 2°.

11.11.12 Pump Unload

The bypass valve includes provisions for limiting inlet-to-bypass differential pressure to 1758.0 kPa (255 psi) with the cutoff valve closed.

11.11.13 T25 Sensing

The control senses T25 by supplying fuel through a fixed orifice to a remote sensor that throttles the fuel and returns it at a differential pressure proportional to temperature.

11.11.14 Metering Valve Position Signal

The control provides an external electrical signal indicating fuel metering valve position.

11.11.15 Transfer Supply

An external port provides servo fuel to the remote transfer valve.

11.11.16 External Servo Supply

An external port provides servo fuel to the air valve actuation servovalves.

11.11.17 Control Pressure Drop

Pressure drop from inlet to outlet is less than 1241 kPa (180 psi) with 5897 kg/h (13,000 pph) flow.

11.11.18 Design Pressure Levels

The control is designed for inlet and outlet pressure of 11,515 kPa (1670 psig) and a bypass pressure of 1172 kPa (170 psig).

11.11.19 PLA Torque

Torque required to operate the PLA is less than 25 lb-inches and there is no self-motoring.

11.11.20 Stator Feedback Loading

The control provides a 44.48 N (10-lb) force to keep the external cable in tension.

11.11.21 Internal Adjustments

The control includes internal adjustments for absolute minimum fuel flow and for maximum core speed.

11.11.22 External Adjustments

Provisions are included for internal adjustment of core idle rpm and for fuel specific gravity.

11.12 HYDROMECHANICAL T25 SENSOR

The hydromechanical T25 sensor is mounted in the engine airflow path behind the fan and operates in conjunction with the fuel control to generate a fuel pressure proportional to sensed air temperature. This is an F101 component. A gas-filled coil senses temperature which expands a bellows inside the sensor body. The bellows applies a force to a beam balance system which changes a flow area, thereby changing the pressure differential.

11.13 TRANSFER VALVE

A two-position transfer valve function is used to select between the primary and the backup control modes of operation. Because of the physical installation limitations, the transfer valve function was partitioned into two separate components identified as the stator transfer valve and the fuel transfer valve. Figure 37 is a schematic of the valves, Figure 54 is a drawing of the fuel flow transfer valve, and Figure 55 is a photograph of the stator transfer valve.

11.13.1 Stator Transfer Valve

This component assembly includes:

- Multiland spool transfer valve
- Latching servovalve
- Spool valve position switch
- Stator system electrohydraulic servovalve

The spool valve is spring-loaded to the primary mode position. In this position the fuel flow to the stator actuation system is provided by the electrohydraulic servovalve as controlled by the digital control. When the latching servovalve is energized to call for backup control, the spool valve moves to the backup position such that fuel flow to the stator actuation system is then provided by the hydromechanical fuel control. In the backup position the electric switch is closed.

11.13.2 Fuel Transfer Valve

This component assembly includes the multiland spool transfer valve and the fuel electrohydraulic servovalve.

The spool valve is spring-loaded to the primary mode position. In this position the fuel flow to the fuel metering valve actuation piston is provided by the electrohydraulic servovalve controlled by the digital control. When the latching servovalve on the stator transfer valve is energized to call for backup control, the spool valve moves to the backup position so that fuel flow to the fuel metering valve actuation piston is provided by the hydromechanical control. This fuel transfer valve assembly is mounted on and is flange ported to the hydromechanical fuel control. Figure 53 shows the valve assembled on the fuel control (lower right side).

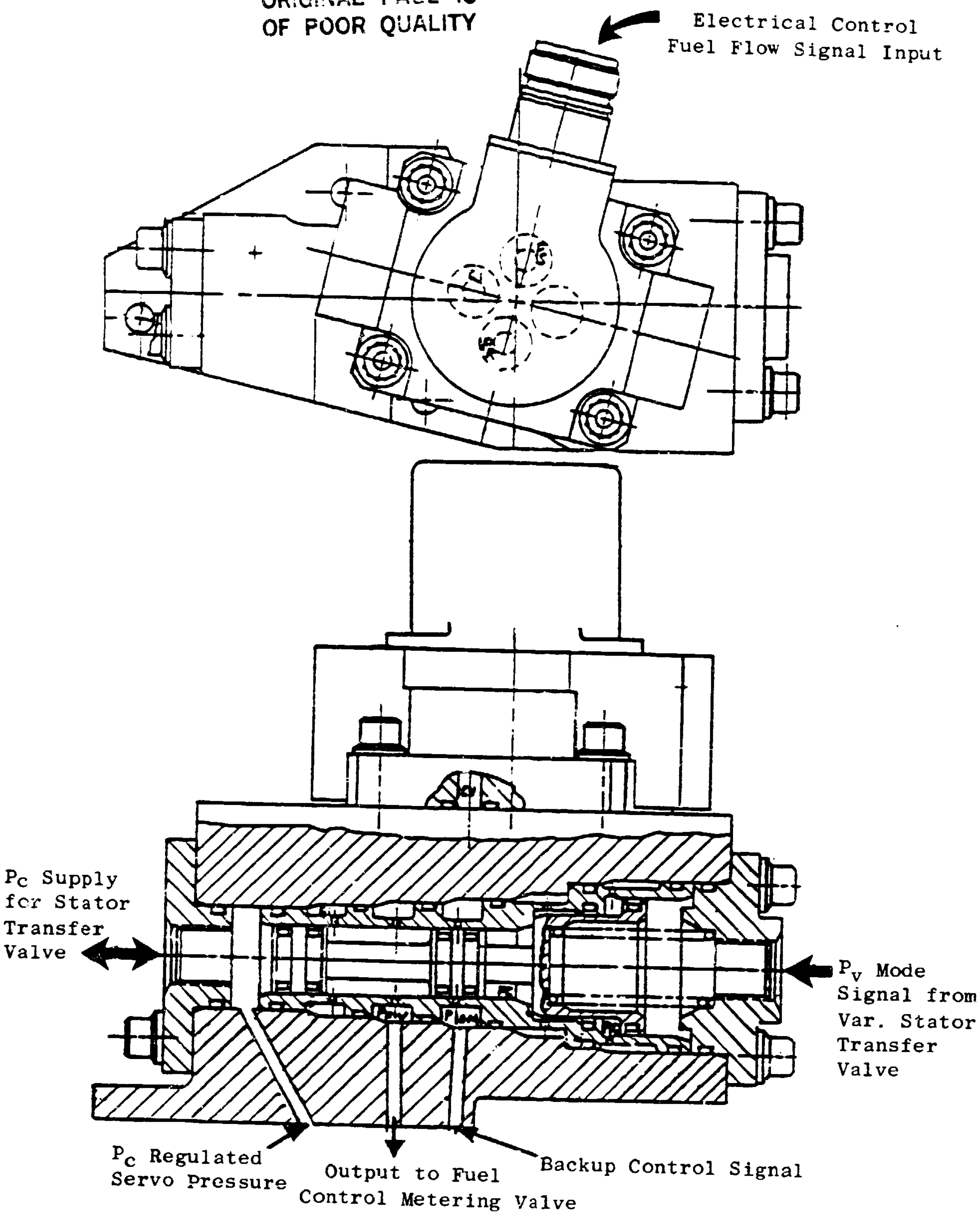


Figure 54. Fuel Flow Transfer Valve.

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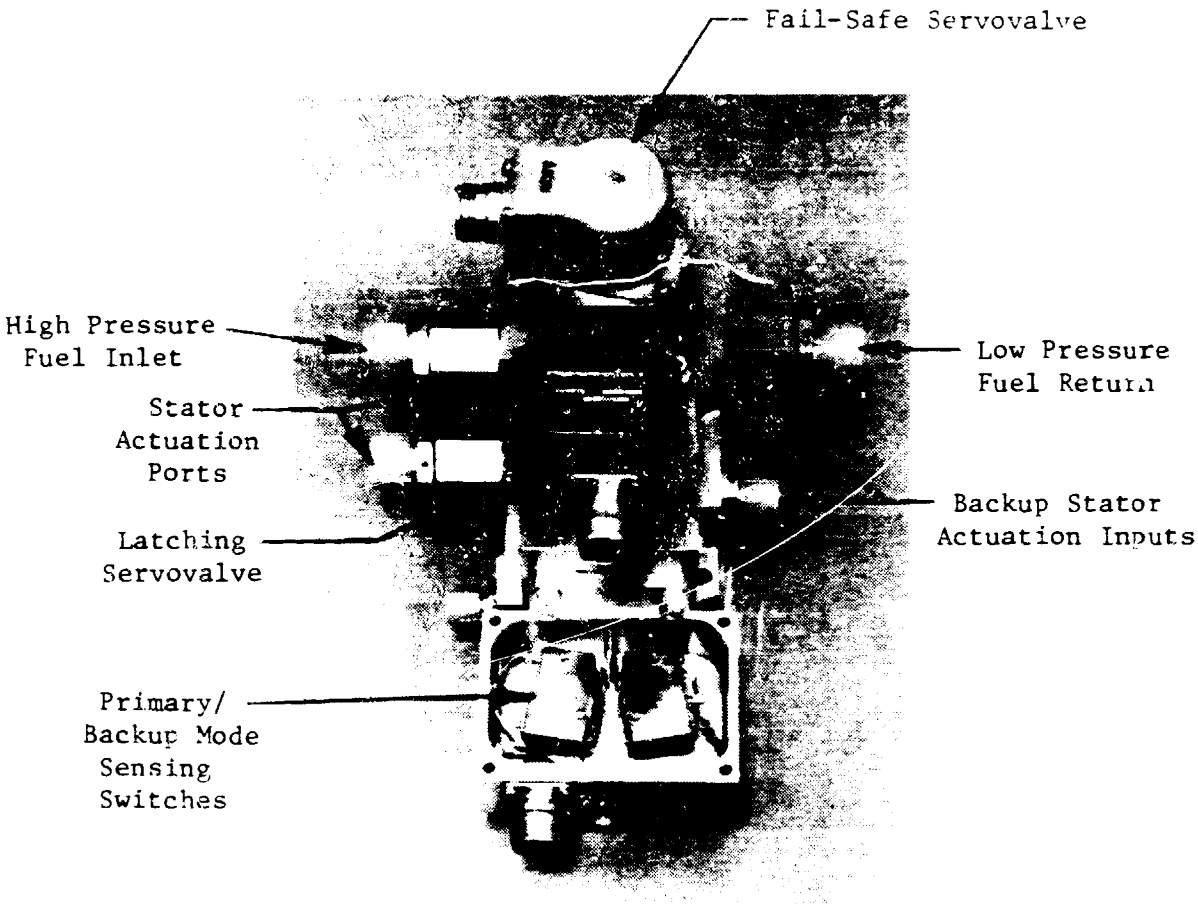

Figure 55. Stator Transfer Valve.

11.14 OVERSPEED PRESSURE SWITCH

This is a differential fuel pressure switch that is used to provide switching logic for backup mode selection in response to an overspeed fuel pressure signal from the hydromechanicl fuel control. Figure 56 shows an outline drawing and a schematic.

Design characteristics of the pressure switch are as follows:

- Switches in the "normal" position for 0 to 448 kPa (0 to 65 psi) differential pressure
- Switches in the "opposite to normal" position for above 7826 kPa (135 psi) differential pressure
- Switches rated for 28 volts, 1 amp operation.

11.15 FUEL PUMP AND FILTER

The fuel pump is V-band and flange-mounted to the accessory gearbox and includes provisions for mounting, flange porting, and driving the fuel control. Refer to Figures 57, 58, and 59. The fuel pump includes: a centrifugal boost element; a positive displacement, vane-type high pressure element; a system pressure relief valve. This is an F101 engine main fuel pump. The fuel filter is a high pressure, cleanabl_-element, barrier-type filter mounted on the fuel pump.

Design characteristics of the fuel pump are listed, and the pump delivers the specified flow at the listed conditions below.

Speed	RPM	6690	6690	4607	1670	670
Inlet Pressure	kPa (psia)	345 (50)	345 (50)	207 (30)	207 (30)	207 (30)
Discharge Pressure	kPa (psia)	7240 (1050)	2620 (380)	2070 (300)	1896 (275)	1896 (275)
Discharge Flow	M^3 (gal/min)	0.174 (46)	0.197 (52 max.)	0.127 (33.5)	0.044 (11.7)	0.015 (4.0)

The boost element pressure rise is 276-345 kPa (40-50 psid) at 6690 rpm.

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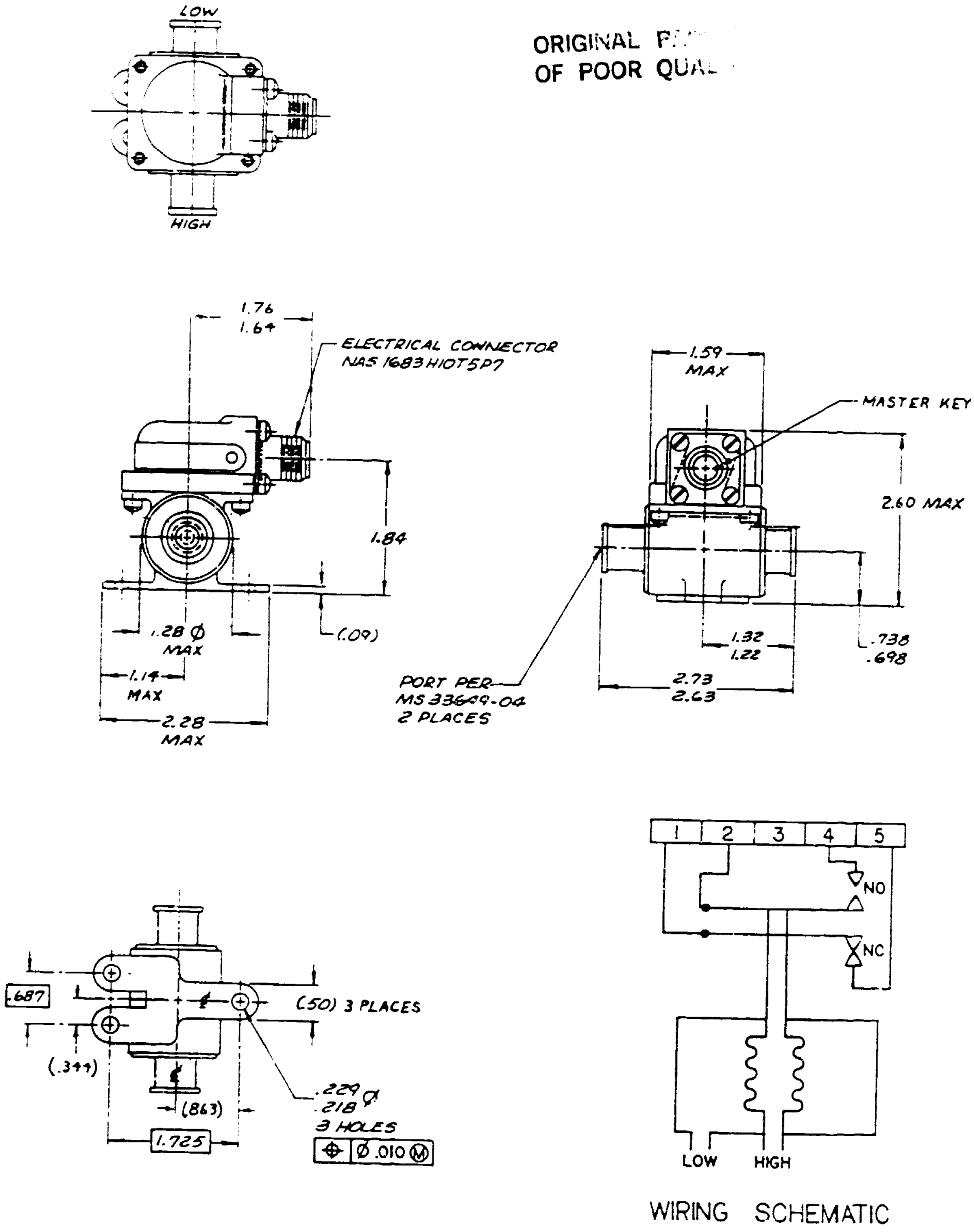

Figure 56. Overspeed Pressure Switch.

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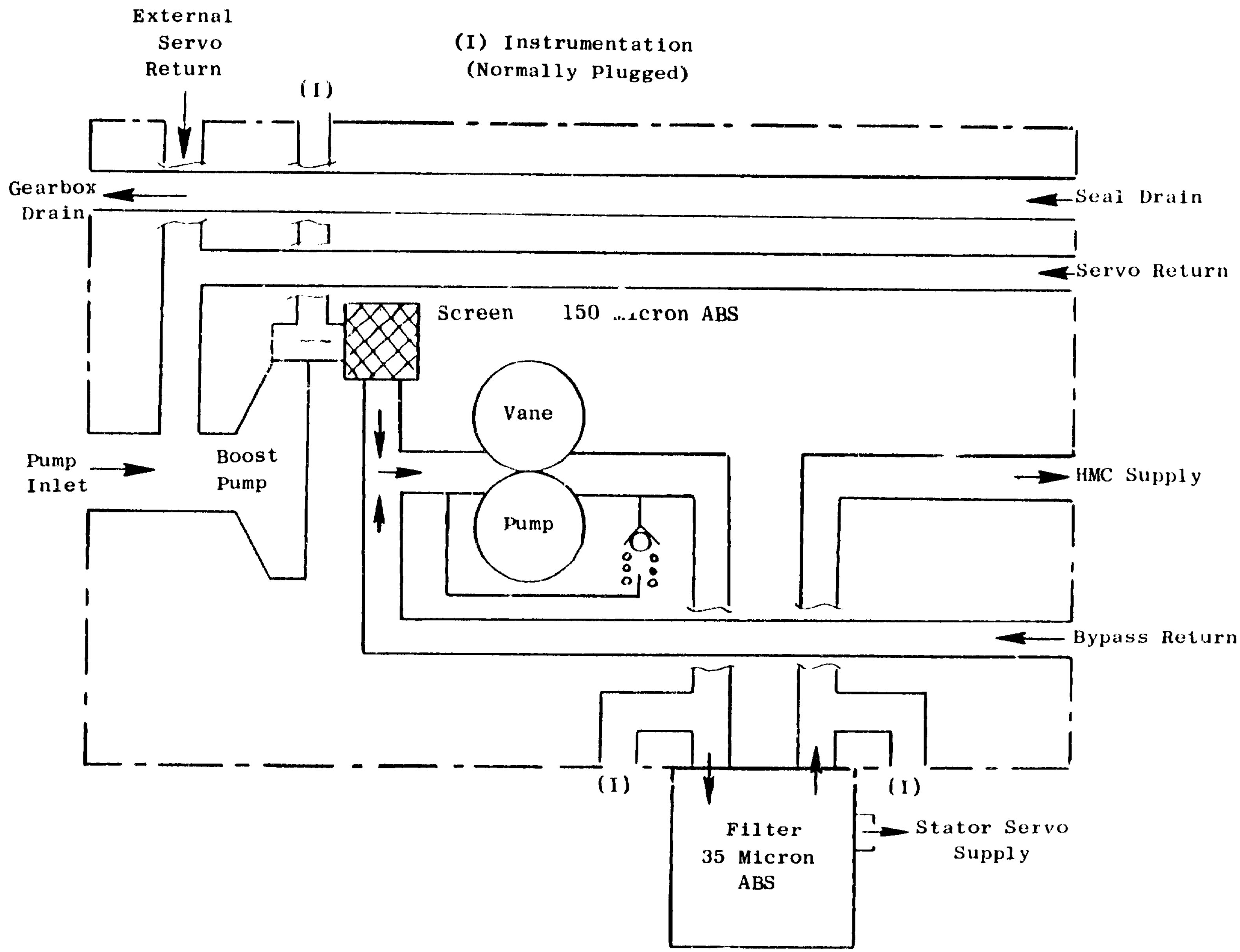

Figure 57. Fuel Pump Porting Schematic.

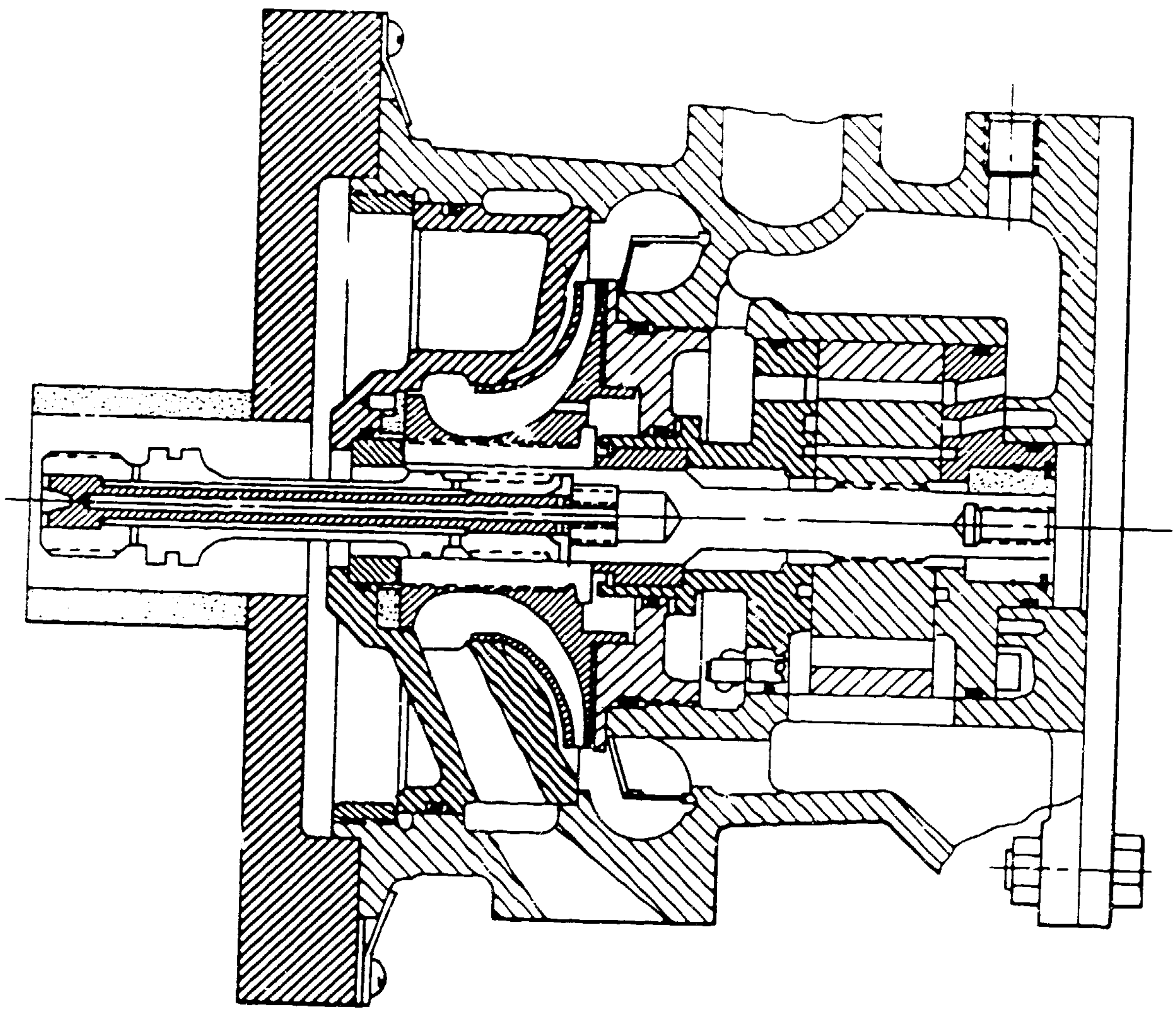

Figure 58. Fuel Vane Pump with Integral Boost and Relief Valve Assembly.

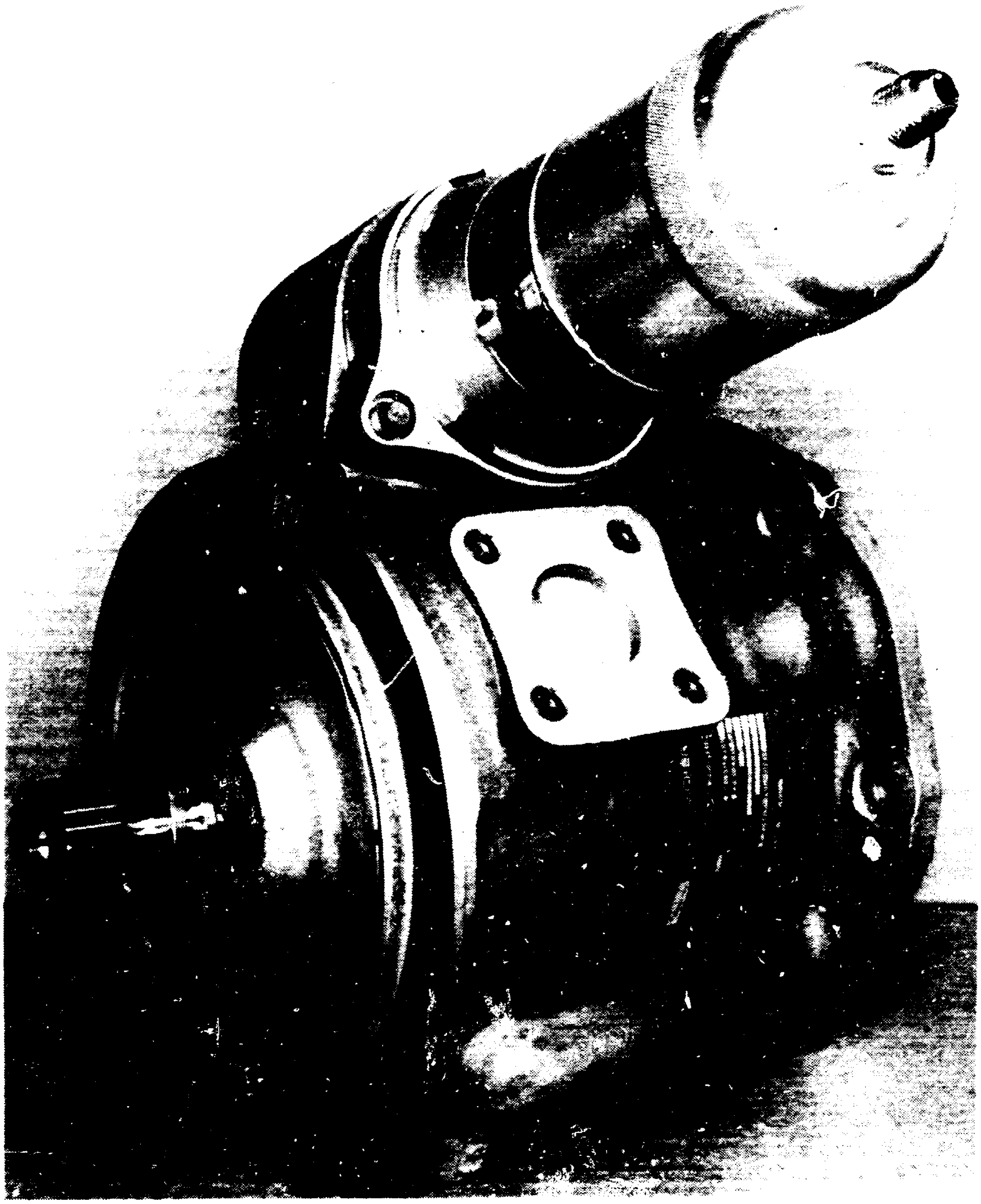

Figure 59. Fuel Pump.

The pressure relief valve is set to bypass fuel from the outlet to the inlet of the high pressure element when the pressure rise exceeds the specified level.

	kPa	psi
• Cracking pressure	8,619	1250
• Rated flow pressure	10,342	1500
• Reseat pressure	8,274	1200

11.16 MAIN ZONE SHUTOFF VALVE

The main zone shutoff valve (MZSOV) is a variable-area valve located in the fuel supply line to the main zone of the double-annular combustor. The valve provides a variable restriction in this line from full open to complete shutoff (Refer to Figures 60 and 61). The unit includes a shaped fuel-flow port, a moveable piston to vary the port area, an electrohydraulic servovalve, and a position sensor. The MZSOV operates closed loop in response to an electric signal from the digital control and provides an electrical valve position feedback signal to the digital control. Refer to Paragraphs 11.3 and 11.4 for descriptions of the servovalves and position transducer.

The servovalve system is biased to cause the valve to move to the open position in the event of signal failure to zero or to maximum level. Further, the movable piston is spring-loaded to the open position.

The design characteristics of the MZSOV are listed as:

Connection	- Fuel in and fuel out - Servo supply and return - Two electrical connectors
Fuel pressure	- 8619 kPa (1250° psig) max.
Fuel temperature	- 380 K (225° F) max.
Pressure drop	- 35 kPa at 5443 kg/h (5 psid at 12,000 pph) full open
Actuation rate	- 10% stroke/sec/mA
Servovalve	- Refer to Paragraph 11.3
Feedback	- Refer to Paragraph 11.4

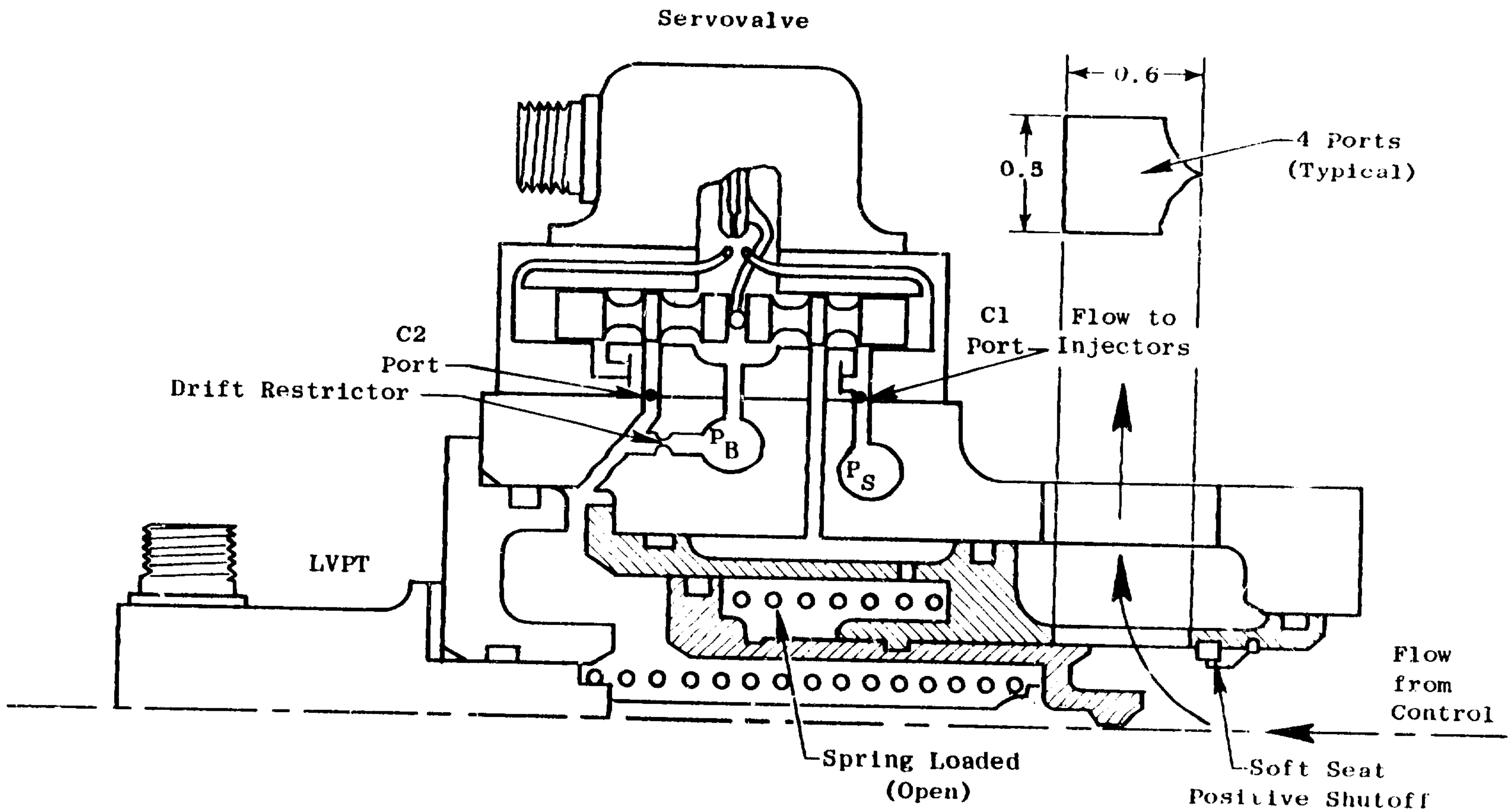

Figure 60. Main Zone Shutoff Valve Schematic.

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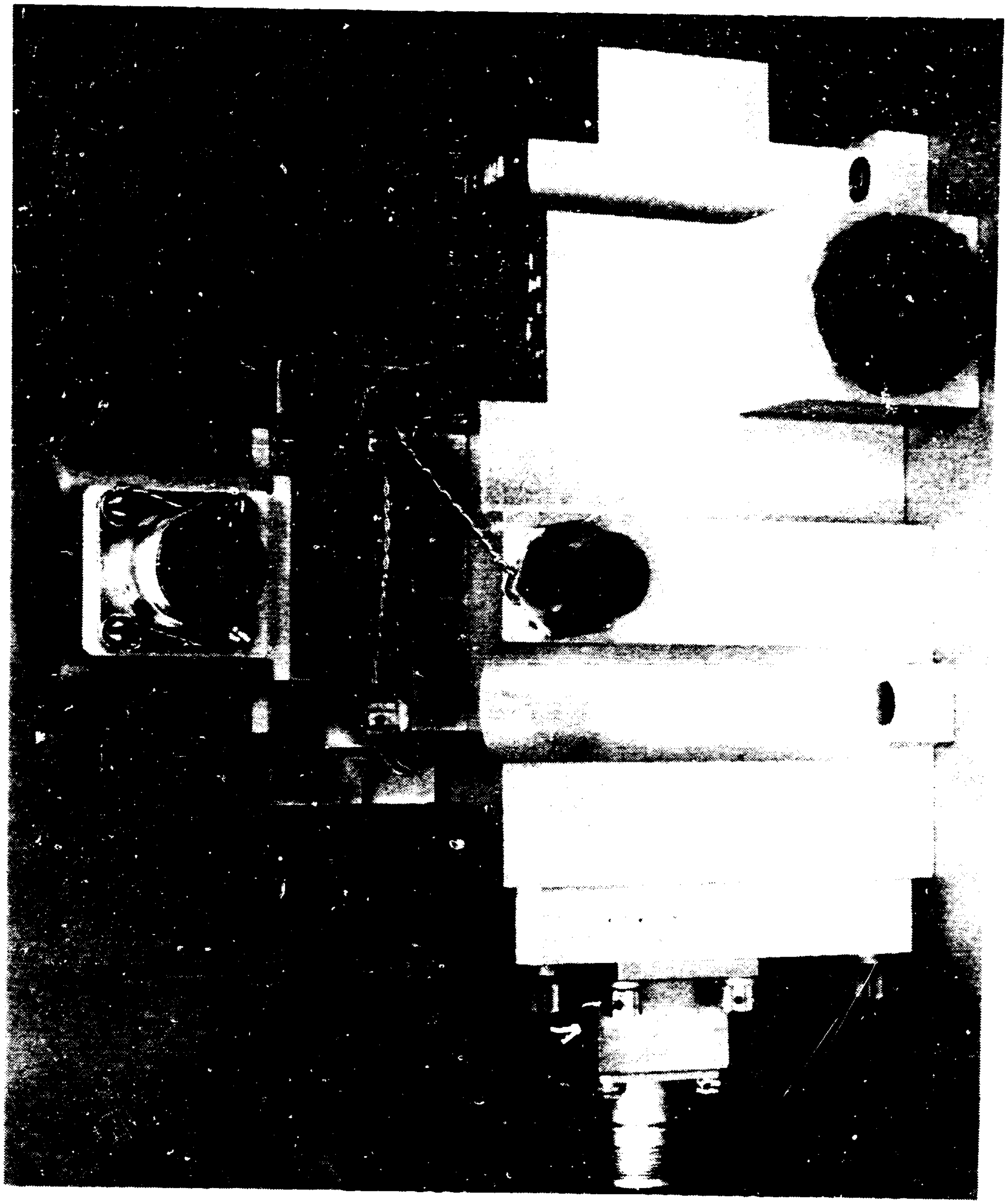

Figure 61. Main Zone Shutoff Valve.

11.17 PILOT ZONE RESET VALVE

The pilot zone reset valve is a two-position valve located in the fuel supply line to the pilot zone of the double-annular combustor. This valve provides two levels of pilot zone fuel flow restriction in this line - full closed or full open. This valve is identical to the main zone shutoff valve described in Paragraph 11.16, except it does not include a position feedback sensor. Figure 62 is a photograph of the valve. The pilot zone reset valve operates open loop in response to an electric signal from the digital control. Refer to Paragraph 11.3 for description of the servovalve.

The servovalve system is biased to cause the valve to move to the open position in the event of loss of electric signal. Further, the movable piston is spring-loaded to the open position.

Connections	-	Fuel in and fuel out
	-	Servo supply and return
	-	One electrical signal
Fuel pressure	-	8619 kPa (1250° psig) max.
Fuel temperature	-	380 K (225° F) max.
Pressure drop	-	35 kPa max. at 5443 kg/h (5 psid max. at 12,000 pph) full open
Actuation rate	-	1% stroke/sec/mA
Servovalve	-	Refer to 11.3

11.18 AIR VALVE ACTUATORS

The air valve actuator is an assembly of a linear hydraulic (engine fuel) piston actuator, a two-stage electrohydraulic servovalve, and an LVPT position feedback transducer. Figure 63 is a schematic of the actuator. This is an F101 IGV master actuator, except modified to include an LVPT instead of an LVDT. Actuators of this type are used on the E^3 for actuation of all three clearance control valves and for the ganged start bleed valves. The design characteristics of the air valve actuator are listed as follows:

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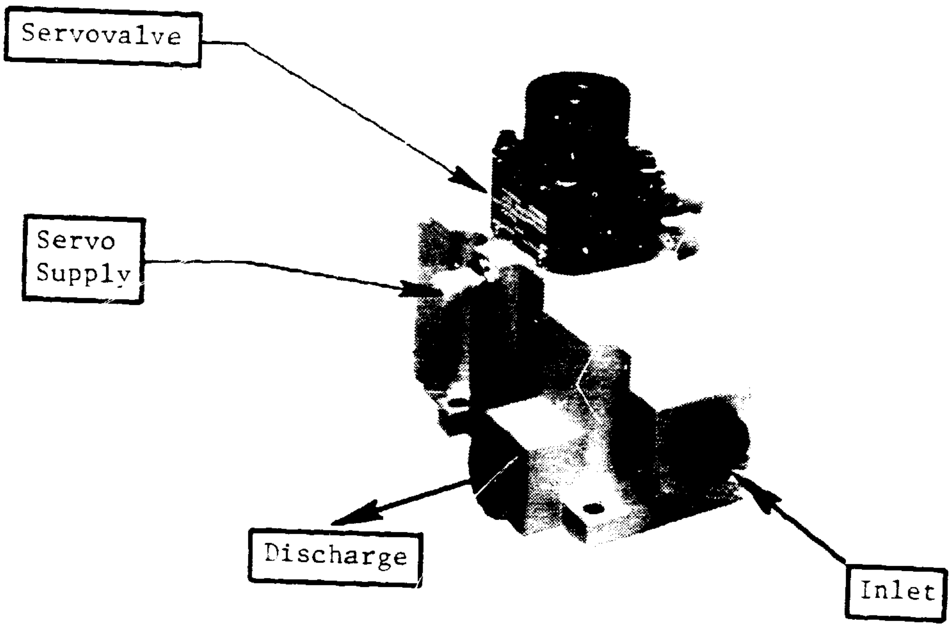

Figure 62. Pilot Zone Reset Valve.

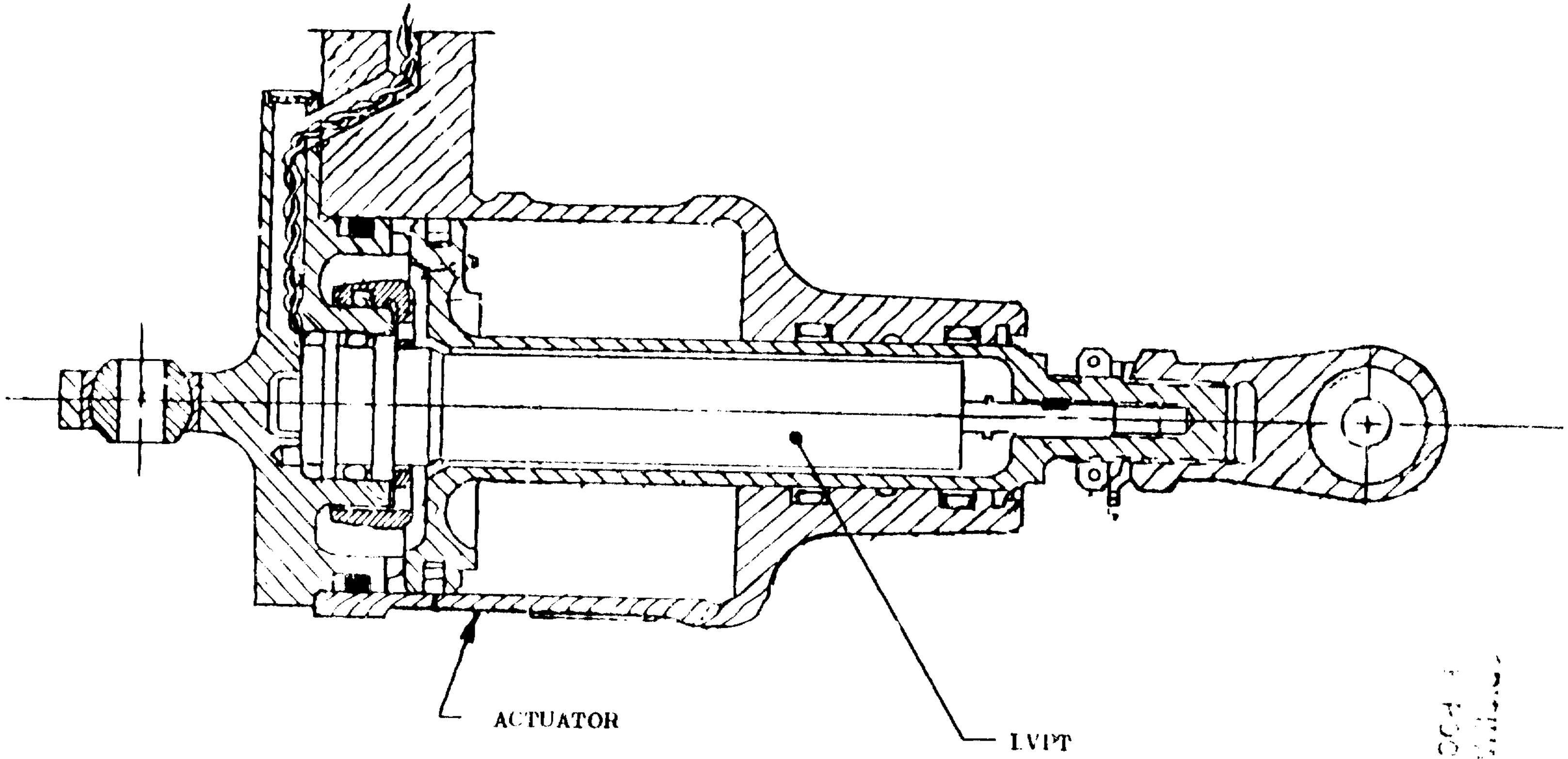

Figure 63. Air Valve Actuator and Position Sensor.

Stroke	3.81 cm (1.5 in.)
Area, head end	20.06 cm^2 (3.11 in^2)
Area, rod end	17.22 cm^2 (2.67 in^2)
Dia, rod	1.905 cm (0.75 in.)
Servovalve	Ref. 11.3, Standard
Feedback	Ref. 11.4

11.19 STATOR ACTUATORS

The stator actuators (two) are fuel-operated, linear piston actuators. These are CF6 actuators, except that the stroke has been modified for the E^3.

Design characteristics of the the stator actuators are listed as:

Area, head end	18.90 cm^2 (2.93 $in.^2$)
Area, rod end	16.90 cm^2 (2.62 $in.^2$)
Stroke	8.072 cm (3.178 in.)

11.20 COMPRESSOR CLEARANCE CONTROL VALVE

The compressor clearance control valve is a continuously variable air valve that has two inlet ports and one outlet port. The valve provides variable-area airflow paths from each inlet port to the common outlet port. Figure 64 is a photograph of the valve and Figure 65 is a cross section.

A rotary valve containing shaped flow ports for both inlet passages is located within the valve body. An external lever attached to the rotary valve axis provides valve rotation in response to linear input from the compressor clearance valve actuator (described in Paragraph 11.18).

	Percent Open	Inlet Pressure, kPa (psia)	Air Temp, K (° F)	Airflow, kg/s (pps)
Inlet A	100	741.2 (107.5)	656 (720)	0.962 (2.12)
	28	850.8 (123.4)	656 (720)	0.386 (0.85)
Inlet B	0	1172 (170)	297 (75)	*
	100	672.3 (97.5)	672 (750)	0.576 (1.27)

*0.227 kg/s (0.5 ppm max.)

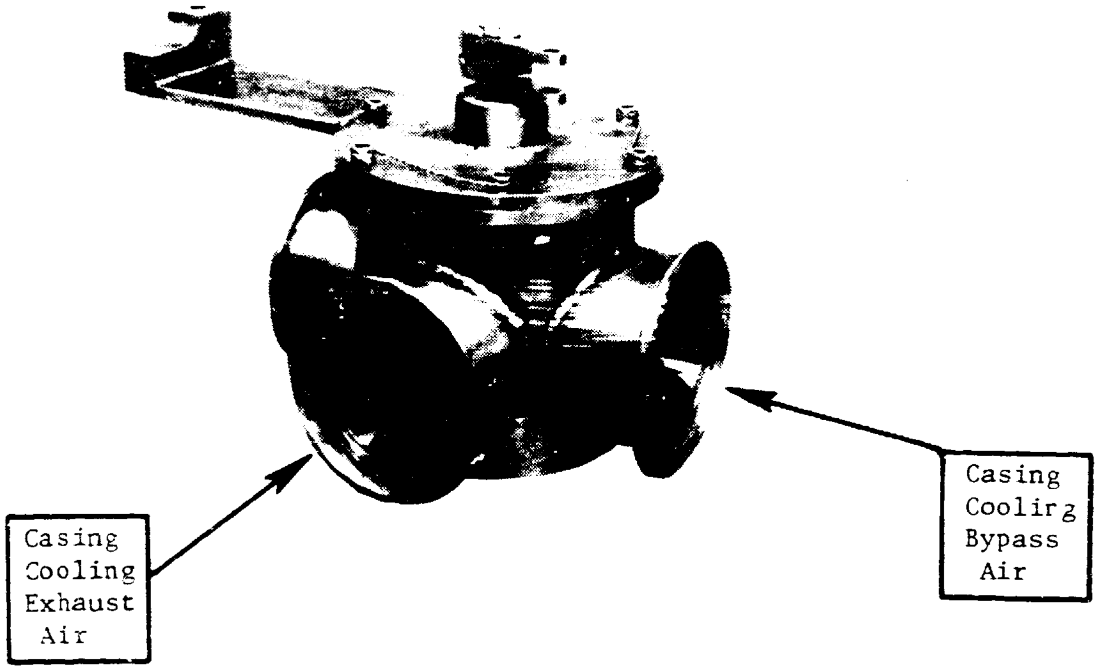

Figure 64. Compressor Clearance Control Valve.

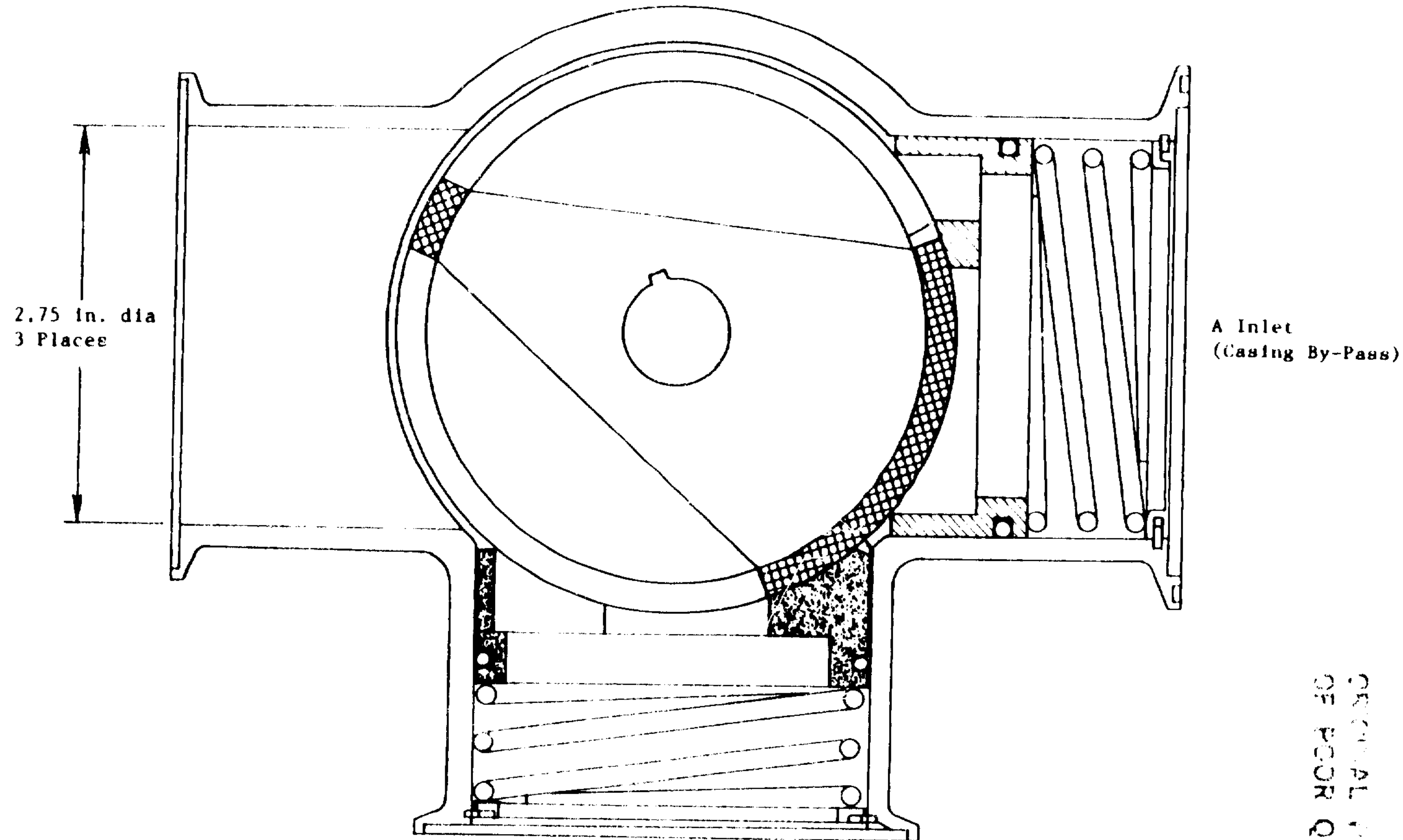

Figure 65. Compressor Clearance Control Valve Cross Section.

11.21 START BLEED VALVE

Start bleed airflow on the E^3 is controlled by four identical 8.89 cm (3.5-in.)-diameter butterfly valves. Figure 66 is a cross section of this valve. The four valves are positioned through a unison ring by an air valve actuator (described in Paragraph 11.18).

Design operation characteristics of the start bleed valve are listed below:

Inlet air temperature	220 to 611 K (65° to 640° F)
Inlet air pressure	103.4 to 689.5 kPa (15 to 100 psia)
Actuation time	1.5 sec
Failure direction	Closed
Airflow	0.376 kg/s, 340 K, 4.82 kPa (0.83 pps, 152° F, 0.7 psig)

11.22 TURBINE CLEARANCE CONTROL VALVES

One 8.89-cm (3.5-in.) diameter butterfly valve identical to the start bleed valve described in Paragraph 11.21 is used in each of the two turbine clearance control systems to control the flow of casing cooling airflow. Each valve is positioned by an air valve actuator as described in Paragraph 11.18.

11.23 START RANGE TURBINE COOLING VALVE

This is a 6.35-cm (2.5-in.), in-line, air actuated poppet valve. Figure 67 shows a cutaway schematic of this valve. Two valves are used for each engine and operated in parallel by a solenoid-driven pilot valve. When the signal port is vented to ambient, valve inlet pressure holds the valve in the closed position shown in Figure 67. When PS3 is applied to the signal port the valve opens. Design characteristics of the valve are listed below.

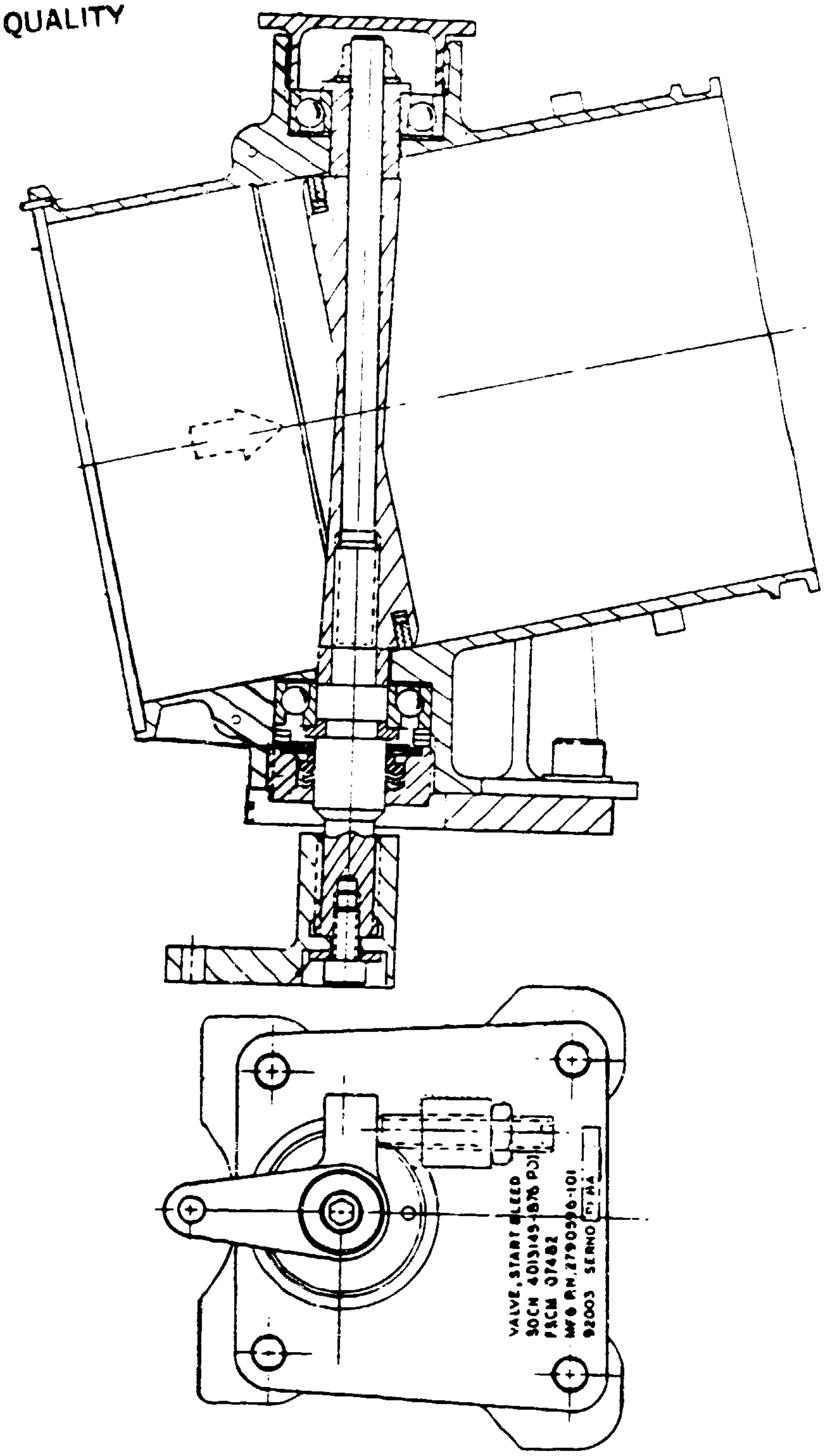

Figure 66. Start Bleed Valve Cross Section.

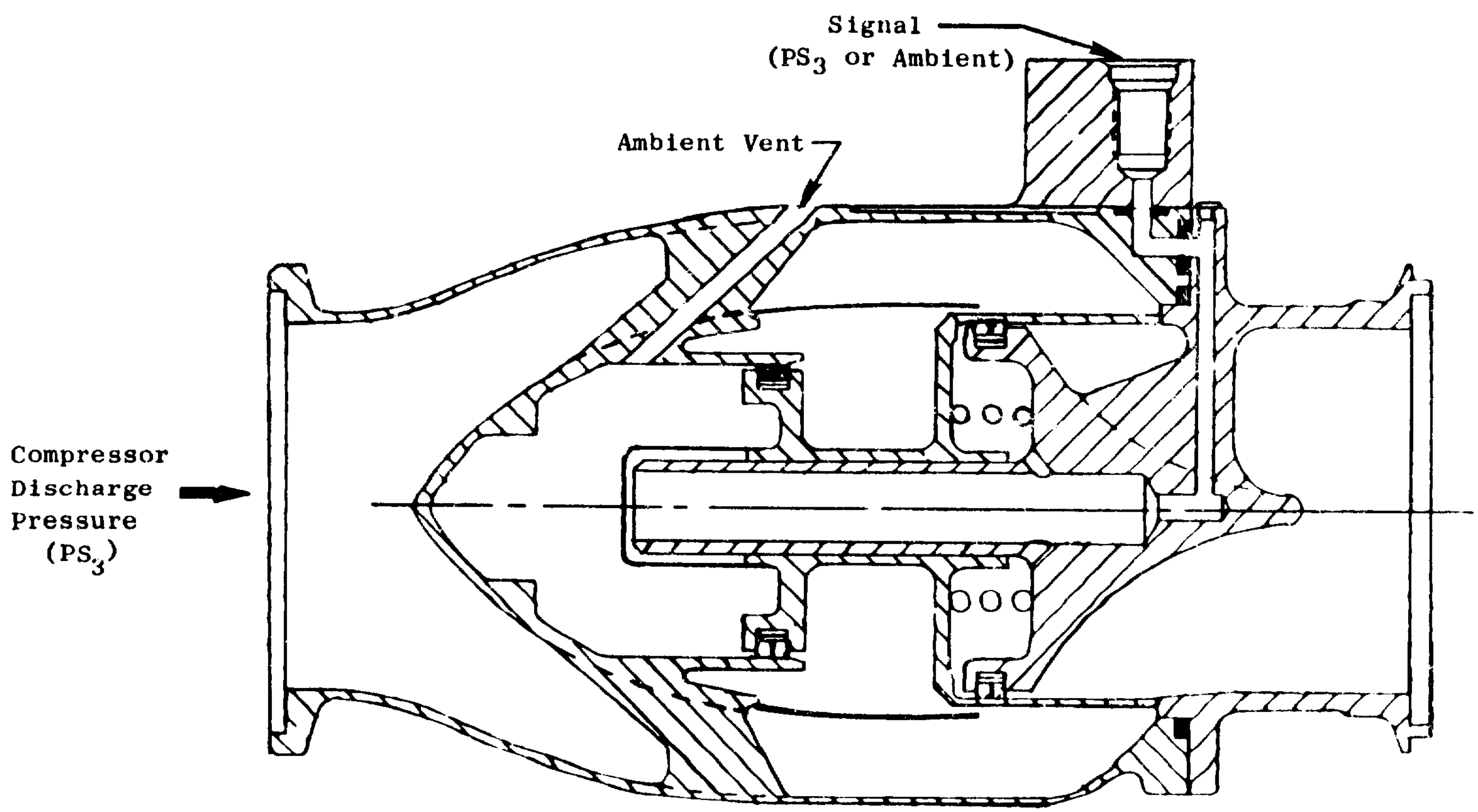

Figure 67. Start Range Turbine Cooling Valve Schematic.

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Inlet air temperature	220 to 505 K (-65° to 450° F)
Inlet air pressure	138 to 414 kPa (20 to 60 psia)
Airflow	0.227 kg/s, 365 kPa, 490 K (0.5 pps at 53 psia, 422° F)
Pressure differential	3.45 kPa (0.5 psi) at design flow
Actuation time	2 sec

1..24 START RANGE TURBINE COOLING SOLENOID

This is a three-way pneumatic solenoid valve that controls the signal pressure to the start range turbine cooling valves described in Paragraph 11.23. Design characteristics of this valve are listed below.

Operating pressure	34.5 to 6895 kPa (5 to 1000 psig)
Temperature - Ambient	220 to 450 K (-65° to 350° F)
- Fluid	220 to 783 K (-65° to 950° F)
- Body	478 K (400° F) Max.
Electrical - Voltage	22-29 volts d.c.
- Current	1.25 amps

11.25 ELECTRICAL CABLES

There are seven on-engine cable assemblies used for interconnecting the various control components and sensors. Generally, AWG 20, stranded, nickel-plated copper wire is used. Functionally, associated wires are run as metal-shielded twisted pairs and triplets within cables consisting of a glass-fiber braid covered by an outer metallic (nickel) braid. Connectors are of stainless steel and are mechanically attached to the outer metallic braid to carry handling loads and provide shielding grounds. Figure 68 shows typical cable construction.

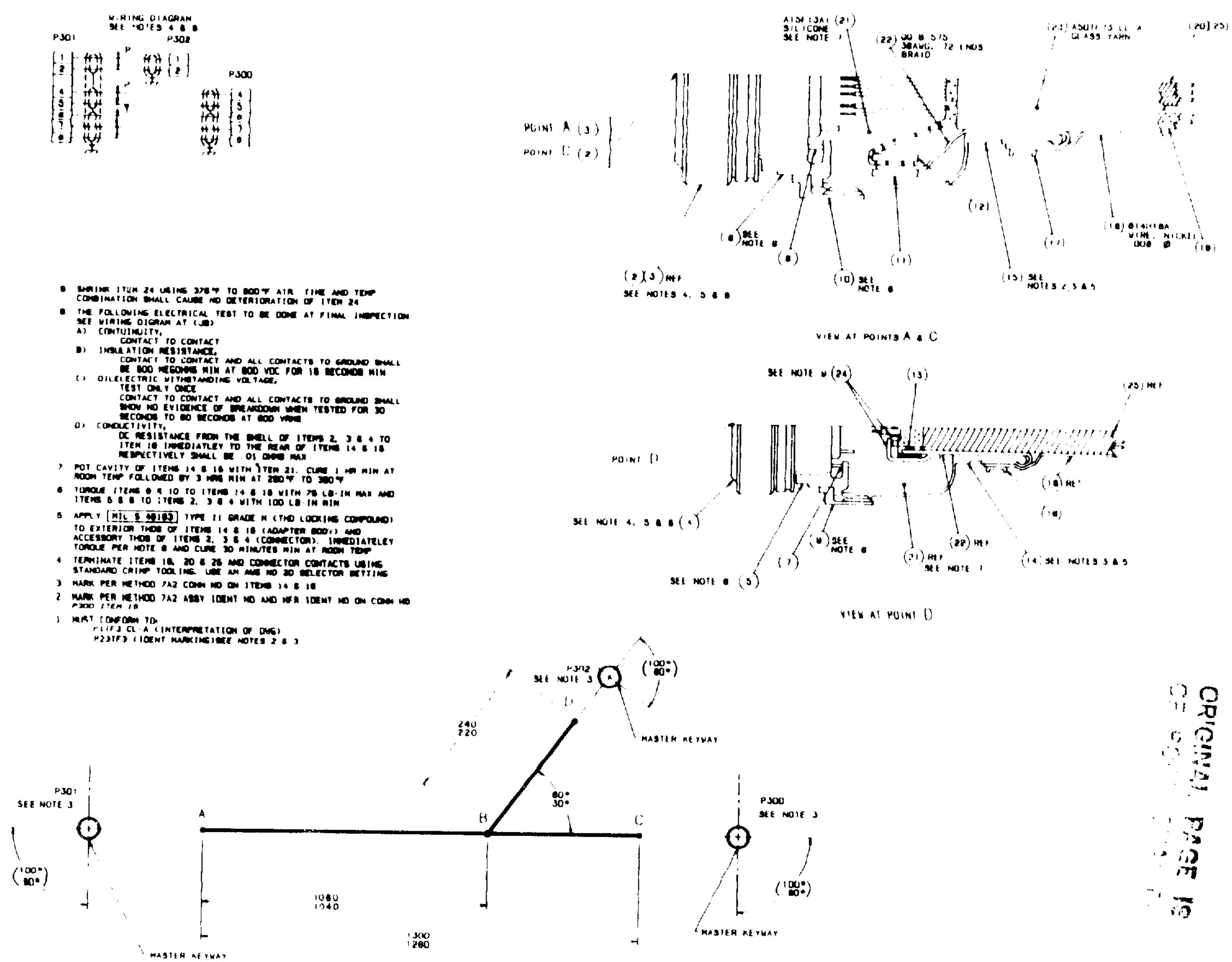

Figure 68. Typical E^3 Electrical Cable.

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12.0 SYSTEM DIFFERENCES FOR CORE ENGINE

The control and fuel system for the core engine will be the same as the ICLS system described in the previous sections of this report, with the following exceptions:

- All LP turbine-related functions and hardware are deleted. Deleted functions are fan speed governing and LPT clearance control. Deleted components are the fan speed sensor, the T12 sensor, and all components involved in LP turbine clearance control.
- The digital control will be an off-engine rather than on-engine configuration. Electrically, the controls will be virtually identical.
- The compressor stator control function will not be used. A test facility control system with individual stage control capability will be used to provide experimental flexibility.
- Only three of the 35 HPT discharge thermocouples (T42) will be used for the control system rather than the five on the ICLS engine. This change was made in order to provide more turbine discharge profile data on the initial engine run, while still providing an adequately averaged, control-dedicated T42 signal.

13.0 SYSTEM DIFFERENCES FOR THE FLIGHT PROPULSION SYSTEM ENGINE

One of the first steps in the E^3 program was the preliminary definition of a production design (termed FPS, Flight Propulsion System). This was done in 1978. The ICLS control and fuel system described in this report was designed to demonstrate FPS technology and, thus, is essentially the same as the currently envisioned FPS or production engine system. The few differences are described below.

1. Ultimately, a single-channel digital control, as on the core and ICLS engines, is considered feasible for a production E^3. However, for initial service, dual redundant controls with hydromechanical overspeed protection (but no other hydromechanical backup) is considered necessary to achieve the desired operational reliability. It is expected that in-service development will ultimately produce a digital control with reliability equivalent to current controls so that redundant controls are no longer necessary.

2. Improvements in digital control power supply size and efficiency will result from the introduction of an FPS alternator tailored to the E^3 digital control. The F101 alternator, used for the core and ICLS to avoid the costly development of a new design, required power supply design compromises.

3. The Waste-Heat Recovery System (WHRS) concept that emerged from early E^3 design studies would probably be included on a production E^3. The WHRS transfers heat from the compressor bleed air (used for aircraft environmental control) to the engine fuel sytem. This system would return energy that is currently wasted to the engine cycle and also would eliminate the need for fan air cooling of the environmental bleed air used in current aircraft. For a typical cruise condition, the design study indicated that the WHRS will provide a net sfc reduction of approximately 0.8%. Figure 69 is a schematic of the WHRS. The system is further described in Reference 2. A modification of the WHRS is described, which can be a help in accommodating future fuels with higher freezing points by providing controlled fuel tank heating.

4. A thrust reverser would be incorporated on a production E^3, and control of the reverser would be performed by the engine control system. The reverser control strategy can be added to the digital control with little effect on the computing elements. The strategy will include the basic reverser sequencing control, interlocks to minimize misdirected thrust during reverse transients, and core stator reset to avoid reingestion-induced engine surge. The reverser is not included in the E^3 demomstrator program, and no detailed actuation or control system design work has been performed for it.

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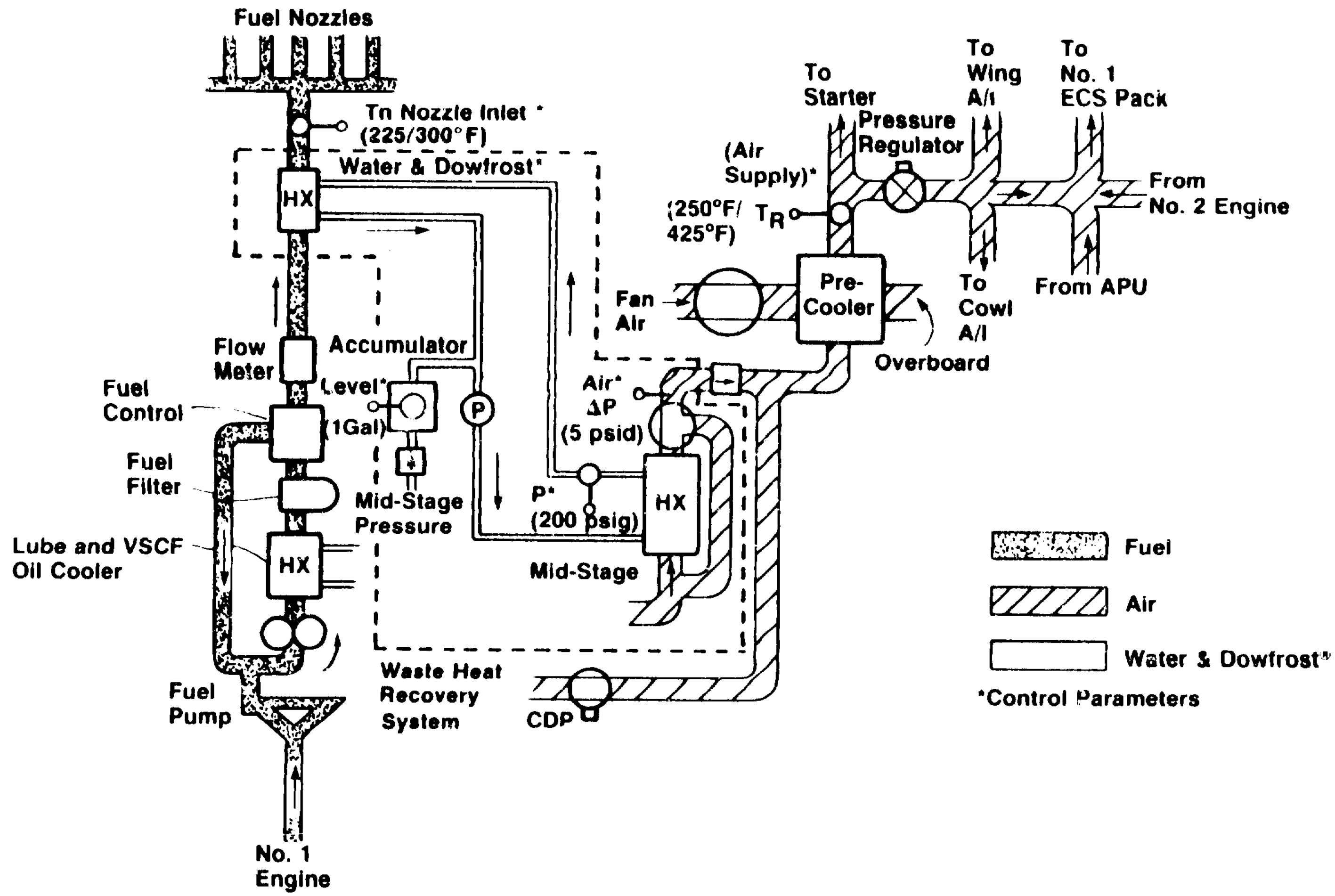

Figure 69. E^3 Waste-Heat Recovery System.

APPENDIX

Instrumentation Set for the Digital Processor Module.

Microcycles*	Operation Code +	Mnemonic	Function
1	0	NOP	No Operation.
7	1	LIX	The most significant nine bits of the index register are loaded from the address field.
2	5	INP	The data bus is loaded into the accumulator. The address field is provided to select the input device. The I/O flag goes low during the instruction.
2	6	OUT	The accumulator is placed on the data bus. The address field selects the output device. The I/O and bus control flags go low during the instruction.
1	7	LDR	The accumulator is loaded from the RAM location selected by the address field.
1	8	LDC1	The accumulator is loaded from the location in the first 512 words of the constants memory selected by the address field.
1	9	LDC2	The accumulator is loaded from the location in the second 512 words of the constants memory selected by the address field.
1	10	ADC1	The location in the first 512 words of the constants memory selected by the address field is added to the accumulator. The carry link is loaded.
1	11	ADC2	The location in the second 512 words of the constants memory selected by the address field is added to the accumulator. The carry link is loaded.
1	12	SBC1	The location in the first 512 words of the constants memory selected by the address field is subtracted from the accumulator. The carry link is loaded.
1	13	SBC2	The location in the second 512 words of the constants memory selected by the address field is subtracted from the accumulator. The carry link is loaded.

* = 1 microcycle = 285.7 ns

\+ = Starting address in program memory is twice the OP Code.

Instrumentation Set for the Digital Processor Module (Continued).

Microcycles*	Operation Code +	Mnemonic	Function
1	14	ADR	The location in the RAM selected by the address field is added to the accumulator. The carry link is loaded.
1	15	SBR	The location in the RAM selected by the address field is subtracted from the accumulator. The carry link is loaded.
2	16	STO	The contents of the accumulator is stored in the RAM location selected by the address field. The accumulator is not changed.
1	17	LDI	The accumulator is loaded with a number represented by the nine bits of the address field. The most significant bit of the address field is spread over the eight most significant bits of the accumulator to provide a 16-bit signed number in the range +255 to -256. The sign-spreading occurs in all cases where the address field is used as a data word.
1	18	ADI	The number represented by the address field is added to the accumulator. The carry link is loaded.
1	19	ADIC	The number represented by the address field is added to the accumulator. The carry-in to this addition is taken fromthe carry link. The carry link is loaded.
1	20	ADRC	The location in the RAM selected by the address field is added to the accumulator. The carry-in to this addition is taken from the carry link. The carry link is loaded.
1	21	SBRC	The location in the RAM selected by the address field is subtracted from the accumulator. The carry-in to this subtraction is taken from the carry link. The carry link is loaded.
1	22	ASE	The address strobe signal goes low for the duration of this instruction. The address field is available for addressing slow I/O devices.
1	23	CHS	The accumulator is loaded with the two's complement of the accumulator. The address field is not used.

Instrumentation Set for the Digital Processor Module (Continued).

Microcycles*	Operation Code	Mnemonic	Function
24	24	MPY	The 16-bit signed number in the accumulator is multiplied by the 16-bit signed number in the RAM selected by the address field. The multiplication is fractional. The most significant 16-bits of the result are located in the accumulator. The least significant bits are in the Q-register. The carry link is left in an arbitrary state. The multiplication of a full-scale negative number by a full-scale negative number produces an overflow condition and should be avoided by the programmer.
1	36	RCLQ	The accumulator is loaded from the Q-register is unchanged.
1	37	RCLX	The accumulator is loaded from the index register. The index register is unchanged.
1	38	PUTQ	The Q-register is loaded from the accumulator. The accumulator is unchanged.
1	39	PUTX	The index register is loaded from the accumulator. The accumulator is unchanged.
36	40	DIV	The signed number in the accumulator is divided by the signed number in the RAM selected by the address field. The division is fractional with the result located in the accumulator. The uncorrected remainder is lost. An overflow condition occurs when the dividend is greater in magnitude than the divisor.
8	58	MAGL	The absolute value of the signed number in the accumulator is limited by the absolute value of the RAM location selected by the address field. The sign of the accumulator is unchanged. The carry link is left in an arbitrary state.
1	62	[illegible]	The contents of the accumulator and the Q-register are shifted right one bit. The sign bit becomes a zero. The address field is not used.
1	63	RSHA	The contents of the accumulator and the Q-register are shifted right one bit. The sign bit is unchanged. The address field is not used.

Instrumentation Set for the Digital Processor Module (Continued).

Microcycles*	Operation Code	Mnemonic	Function
3	64	ADRL	The RAM location selected by the address field is added to the accumulator. If overflow is detected the accumulator is loaded with a full-scale number of the correct sign. The carry link is not loaded.
3	66	SBRL	The RAM location selected by the address field is subtracted fromthe accumulator. If overflow is detected the accumulator is loaded with a full-scale number of the correct sign. The carry link is not loaded.
3	68	ADRCL	The RAM location selected by the address field is added to the accumulator. The carry-in to this addition is taken from the carry link. If overflow is detected, the accumulator is loaded with a full-scale number of the correct sign. The carry link is not loaded.
3	70	SBRCL	The RAM location selected by the address field is subtracted from the accumulator. The carry-in to this subtraction is taken from the carry link. If overflow is detected, the accumulator is loaded with a full-scale number of the correct sign. The carry link is not loaded.
1	72	LSH	The contents of the accumulator are shifted left one bit. The least significant bit becomes a zero. The address field is not used.
1	73	LSHQ	The contents of the double-length register formed from the accumulator and Q-register is shifted left one bit. The least significant bit of Q becomes a zero. The address field is not used.
4	74	ABS	The accumulator is loaded with the absolute value of the signed number in the accumulator. The address field is not used.
3	76	SMP	The accumulator is loaded with the most positive of the accumulator and the RAM location selected by the address field. The jump flag is set if the RAM data is selected and cleared if the accumulator is selected.
3	78	SMN	The accumulator is loaded with the most negative of the the accumulator and the RAM location selected by the address field. The jump flag is set if the RAM data is selected and cleared if the accumulator is selected.

Instrumentation Set for the Digital Processor Module (Continued).

Microcycles*	Operation Code	Mnemonic	Function
11	80	RINT	An instruction used to return from a priority vector interrupt. The instruction restores the preinterrupt contents of the program counter and status register. The out Ø and rint instructions are the overhead burden associated with the return from interrupts.
1	86	AND	The accumulator is loaded with the per bit logic "and" of the accumulator and RAM location selected by the address field.
1	87	OR	The accumulator is loaded with the per bit logic or of the accumulator and RAM. location selected by the address field.
1	88	XOR	The accumulator is loaded with the per bit logic exclusive or of the accumulator and RAM location selected by the address field.
1	89	NOT	The accumulator is loaded with the 1's complement of its contents. The address field is not used.
1	90	SBA	The accumulator is subtracted from the contents of the RAM location selected by the address field. The result is stored in the accumulator. The RAM is unchanged. The carry link is loaded.
1	91	SBAC	The accumulator is subtracted from the contents of the RAM location selected by the address field. The result is stored in the accumulator. The carry-in to this subtraction is taken from the carry link. The RAM is unchanged. The carry link is loaded.
3	93	LSHQL	The contents of the double-length register formed from the accumulator and Q-register is shifted left one bit. If the sign bit changes, the accumulator is loaded with a full-scale number of the correct sign.
1	94	SFG	The jump flag is set.
1	95	CFG	The jump flag is cleared.

Instrumentation Set for the Digital Processor Module (Continued).

Microcycles*	Operation Code	Mnemonic	Function
6	96	JFG	If the jump flag is set, the program counter is loaded with the current location plus the signed number represented by the address field. At the time of execution, the program counter has already been incremented making the range of accessible addresses +256 to -255, relative to the location of the JFG instruction.
6	99	JRPP	If the sign of the accumulator is positive, the program counter is loaded with the current loaded plus the signed number represented by the address field.
6	102	JRPZ	If the accumulator contains all zeros, the program counter is loaded with the current location plus the signed number represented by the address field.
6	105	JRPN	If the sign of the accumulator is negative, the program counter is loaded with the current location plus the signed number represented by the address field.
6	108	JRP	The program counter is loaded with the current location plus the signed number represented by the address field.
5	111	JRXP	If the sign of the accumulator is positive, the program counter is loaded with the index register plus the address field.
5	114	JRXZ	If the accumulator contains all zeros, the program counter is loaded with the index register plus the address field.
5	117	JRXN	If the sign of the accumulator is negative, the program counter is loaded with the index register plus the address field.
8	120	RTN	The program counter is loaded with the location of the instruction following the jump to subroutine instruction. This instruction returns from subroutines. If the return instruction is used five times without intervening subroutine calls, the program counter is loaded with all zeros.

Instrumentation Set for the Digital Processor Module (Concluded).

Microcycles*	Operation Code	Mnemonic	Function
8	124	JMS	The current contents of the program counter are stored in a push-down stack for use by the return instruction. The program counter is loaded with the index register plus the address field. The stack is deep enough to allow four JMS instructions before information is lost out the bottom of the stack.
5	126	JRX	The program counter is loaded with the index register plus the address field.
2	127	JMD	A double occurrence of this operation code clears the program counter.

REFERENCES

1. Boerstler, L.H., "Control Mode Analysis for the E^3 Engine," General Electric Company Report No. R78AEG646, 15 December 1978.

2. Coffinberry, G.A., "Waste-Heat Recovery System," General Electric Company Report No. R81AEG805, December 1981.

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